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Carbon stocks for six different land use classes in Niassa province, Mozambique

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Thesis submitted for a M.Sc. degree in forest sciences

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Tiivistelmä/Referat – Abstract

The most extensive dry forest and woodland formation in sub-Saharan Africa, including Mozambique, is formed by miombo woodlands. Because of their wide distribution, the miombo woodlands carry significance in global carbon cycle. Previous studies have indicated that while the miombo aboveground carbon stocks appear modest in comparison with tropical rainforests, they have a potential to retain high stocks of soil organic carbon. The miombo landscape is nowadays characterized by widespread deforestation and forest degradation, with woodlands being replaced by anthropogenic land uses such as small-scale agriculture and charcoal harvesting. A new land use type spreading in northern Mozambique is formed by industrial forest plantations. The emerging plantations further change the landscape in transition, allegedly affecting the carbon stocks in the process as well.

The purpose of this study was to quantify carbon stocks on locally relevant land use classes in Niassa province, northern Mozambique, and evaluate the change of carbon stocks caused by forest plantations. Six major land use classes were identified: dense miombo, open miombo, other woody vegetation, fallow land, eucalypt plantations and pine plantations. A sample plot grid was laid on chosen areas representing each of the classes. Vegetation aboveground carbon stocks (trees, shrubs and herbaceous vegetation) were recorded in the inventory and topsoil (30 cm) was sampled for soil organic carbon content, to be determined in laboratory. Vegetation belowground carbon stocks were calculated based on existing root to shoot ratios. Since plantations were generally juvenile on the study area, their average yield during rotation period was estimated based on growth models to provide comparable results.

Forest plantations were found to have carbon stocks of the same order of magnitude as the two miombo land use classes. Open and dense miombo carried mean vegetation aboveground carbon stocks of 27.47 ± 5.77 and 37.65 ± 7.20 Mg ha^{-1} respectively, and mean total carbon stocks of 67.81 ± 17.09 and 86.81 ± 18.91 Mg ha^{-1} respectively, which was consistent with pre-existing results. Pine plantations placed in between with a partially modelled total aboveground mean carbon stock of 34.59 Mg ha^{-1}, whereas the corresponding figure for eucalypt plantations was 21.04 Mg ha^{-1}. Dense miombo had the highest mean total carbon stock of all the land use classes, and fallow land the smallest with 42.59 Mg ha^{-1}. Soil organic carbon did not demonstrate statistically significant differences between any of the land use classes. The result was unexpected, and may be explained either by (i) limited time frame since the land use conversions or (ii) soil mineralogical properties buffering carbon stock changes.

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Miombo woodlands, forest plantations, land use conversion, carbon stocks, forest degradation

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Tiivistelmä/Referat – Abstract

Saharan eteläpuolisen Afrikan laajimman kuivan metsän tyypin muodostavat miombometsät (puustoinen savanni). Näin on myös Pohjois-Mosambikissa. Laajan levinneisyytensä takia miombolla on merkitystä globaalissa hiilen kierossa. Aikaisempien tutkimusten mukaan miombon maanpäälliset hiilivarastot ovat pienehköjä verrattuna trooppisiin sademetsiin, mutta maaperän orgaanisen hiilen varastot voivat olla huomattavan suuria. Miombometsille on nykyisin tyypillistä nopea metsien rappeutuminen ja metsäkato ihmisen toiminnan seurauksena. Korvaavia maankäyttömuotoja ovat mm. leviävä maanviljely ja puuhiilen valmistus, mutta Pohjois-Mosambikissa uutena ilmiönä yhä enemmän myös teolliset metsäplantaasit. Kasvavilla metsäplantaaseilla on vaikutuksensa paitsi maisemaan, myös oletettavasti sen hiilivarastoihin.

Tämän tutkimuksen tarkoituksena oli määrittää hiilivarastojen koko keskeisille maankäyttömuodoille Niassan provinssissa Pohjois-Mosambikissa ja tarkastella siten metsäplantaasien aiheuttamia hiilivarastojen muutoksia. Tutkimuksessa jaoteltiin kuusi maankäyttöluokkaa: tiheä miombo, avoin miombo, muu metsäkasvillisuus, kesantomaa, eukalyptusplantaasit ja mäntyplantaasit. Kenttämittauksiin valittiin jokaista luokkaa edustavat otanta-alueet, joille tehtiin systemaattinen koealaverkko. Suoritetussa inventaariossa määritettiin kasvillisuuden maanpäällisen hiilen osavarastot (puut, pensaat ja ruohokasvillisuus) sekä otettiin maaperänäytteitä maaperän orgaanisen hiilen määritystä varten. Kasvillisuuden maanalainen hiilivarasto laskettiin olemassaolevien juuri-verso -suhteiden perusteella. Koska tutkimusalueen metsäplantaasit olivat pääosin hyvin nuoria, niiden kasvu ja tuotos kiertoajan aikana ennustettiin perustuen malleihin. Näin saatiin vertailukelpoiset tulokset.

Tulokset osoittivat, että metsäplantaasien hiilivarastot olivat suuruusluokaltaan verrattavissa miombometsiin. Avoimen ja tiheän miombon maanpäälliset hiilivarastot olivat keskimäärin 27,47 ± 5,77 ja 37,65 ± 7,20 Mg ha^{-1}, ja kokonaishiilivarastot 67,81 ± 17,09 ja 86,81 ± 18,91 Mg ha^{-1}, mikä vastasi koko lailla muiden tutkimuksien tuloksia. Mäntyplantaasit sijoittuivat edellisten väliin osin mallinnetulla maanpäällisen hiilen keskimääräisellä varastolla 34,59 Mg ha^{-1}, ja eukalyptusplantaaseilla vastaava luku oli 21,04 Mg ha^{-1}. Suurin keskimääräinen kokonaishiilivarasto oli tiheällä miombolla ja pienin kesantomaalla, 42,59 Mg ha^{-1}. Maaperän orgaaninen hiili ei eronnut tilastollisesti merkitsevästi maankäyttöluokkien välillä. Tulos oli odottamaton, ja selityksenä on mahdollisesti joko (i) lyhyt maankäytön muutoksista kulunut aika tai (ii) maaperän rakenne ja minerologiset ominaisuudet hiilen sitojana.

Avainsanat – Nyckelord – Keywords

Miombo-savannimetsä, metsäplantaasit, maankäytön muutos, hiilivarastot, metsäkato

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
BA	Basal area
BCEF	Biomass conversion and expansion factor
BD	Bulk density
BM	Biomass
C	Carbon
DBH	Diameter at breast height
EuP	Eucalypt plantation
FaL	Fallow land
GPS	Global positioning system
IFN	Inventário Florestal National
IPCC	Intergovernmental Panel on Climate Change
LUC	Land use class
MDe	Dense miombo
MOp	Open miombo
NWFP	Non-wood forest product
OWV	Other woody vegetation
PiP	Pine plantation
R:S	Root to shoot
S.D.	Standard deviation
SI	Site quality index
SOC	Soil organic carbon
UEM	Eduardo Mondlane University

1. INTRODUCTION

1.1 Background

1.1.1 Miombo landscape of southern Africa

General features and distribution

The majority of sub-Saharan Africa is dominated by a variety of dry forests and woodlands as the natural vegetation, ranging from semi-arid to sub-humid types (Chidumayo & Marunda 2010). The most characteristic of these types, occurring between the tropical rainforests of Congo basin and the grasslands of the southernmost part of the continent (White 1983), is miombo woodland. It is sometimes referred to as Zambezian woodland, but most often simply as miombo.

Generally, miombo woodlands are closed or partially closed, deciduous savanna-like tropical dry woodland formations with slight to full seasonal behavior (Campbell et al. 1996; White 1983). Miombo can be classified either as forest, woodland or savanna, depending on the context and definition applied. This problem is coherently discussed by Campbell et al. (1996), and results from the heterogenic vegetation structure of trees, shrubs and grasses overlapping with multiple definitions that is a typical feature of miombo. One of the latest classifications is by Timberlake et al. (2010), who classify miombo as “warm mesic dry woodlands”. Miombo represents a climax vegetation type, even though lots of it has been modified by presence of shifting cultivation and anthropogenic fires (White 1983).

White (1983) has presented the most recent and arguably the most commonly referred spatial distribution of the miombo woodlands based on floristic attributes. The illustration in Figure 1 is based on his mapping. The miombo region is estimated to cover 2.4–2.7 million km^2 in seven different countries of southern Africa (Dewees et al. 2011; Frost 1996), making it perhaps the most widespread dry forest and woodland formation even in global terms (Frost 1996). However, it has been noted (Dewees et al. 2011) that the estimated area represents the botanical region of miombo woodlands rather than the actual woodland distribution, which has been drastically reduced by processes of forest degradation and land use conversion.

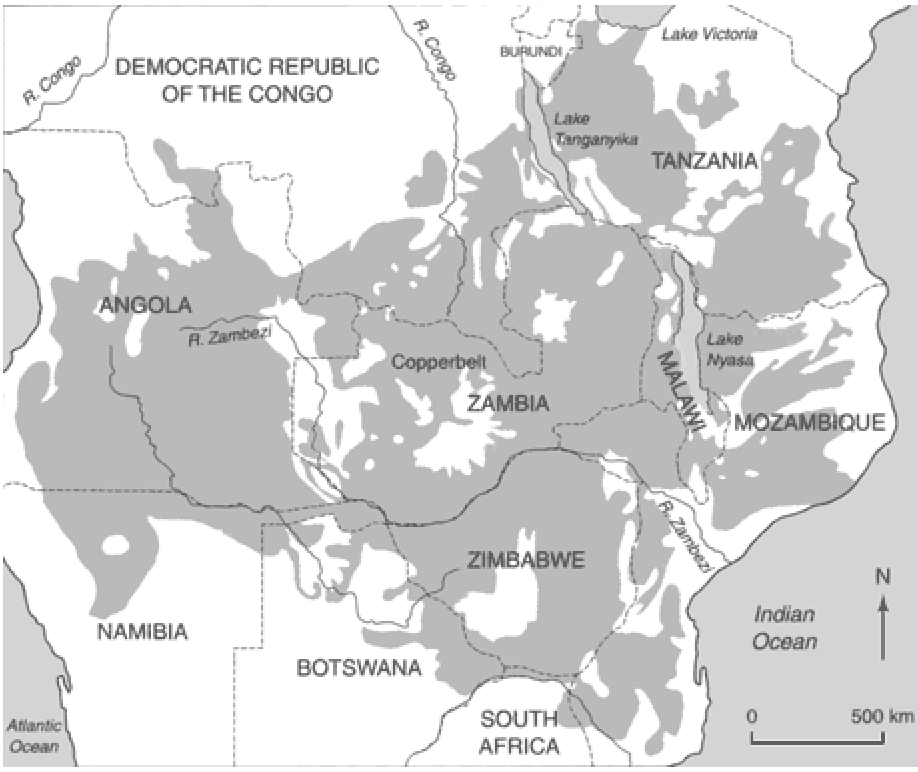

Figure 1. Distribution of miombo woodlands. The figure is based on presentation by White (1983). Source of the picture: [http://www.mpingoconservation.org/index.php?id=60]

The areas on which miombo generally appear have mean annual rainfall ranging from 650 to 1400 mm (Campbell et al. 1996). The climate is strongly seasonal, with the annual rainfall occurring either predominantly or almost completely during a rainy season of 4–5 months (Timberlake et al. 2010; White 1983). The related soils are of old geologic origin and hence nutrient-poor (Campbell et al. 1996) and acid (Timberlake et al. 2010; Frost 1996), and typically also well drained (Frost 1996; White 1983).

Biodiversity

Miombo woodlands form the majority, circa 70 % (Ribeiro et al. 2008a), of the Zambezian regional center of endemism as it is defined by White (1983). It is also referred to as the Zambezian phytoregion. The area is the largest of the seven regional centers of endemism White (1983) presents for mainland Africa, and according to his estimate, houses the highest total number of plant species and a high level of species endemism in Africa as well (8500 and 54 %, respectively). Even though these figures have later been challenged by Linder et al. (2005) presenting significantly smaller estimates (1725 and 22 %), the Zambezian phytoregion stands among the two most important areas in Africa in terms of plant species count and endemism in both studies.

As the Zambezian phytoregion as a whole, also miombo woodlands are considered to house significant plant biodiversity (Dewees et al. 2011; Frost 1996). Yet the richness of species is not distributed evenly. White (1983) divided miombo woodlands further into two classes, the occurrence of which is related to the mean annual rainfall: floristically rich wetter miombo and floristically poor drier miombo. Areas featuring the former typically receive annual rainfall above 1000 mm, whereas areas featuring the latter typically remain below this figure.

Despite the total floristic biodiversity being high on miombo, the relative diversity of woody species and tree species especially does not reach equally high levels. Biodiversity indices for woody plants both high (Giliba et al. 2011) and mediocre (Williams et al. 2008; Isango 2007) have been recorded. The tree species composition is dominated by only three genera with a limited set of species: *Brachystegia*, *Julbernardia* and *Isoberlinia* (White 1983). The most dominant genus throughout the miombo is *Brachystegia* alone or accompanied by either of the two latter (Frost 1996; White 1983). Many of the *Brachystegia* species are called “miombo” in the local languages, hence the name miombo woodlands.

While all of the three dominant genera are utmost characteristic for miombo woodlands, they are rarely encountered outside of them (White 1983). This makes a clear distinctive feature of miombo, all the way to the physical appearance (Campbell et al. 1996; White 1983). A *Brachystegia* tree of typical form is shown in Figure 2. A total of 19 species of *Brachystegia* appear as miombo dominants, however unevenly distributed across the miombo ecoregion (White 1983). The other two genera are only represented by *Julbernardia globiflora*, *Julbernardia paniculata* and *Isoberlinia angolensis* as dominant species (Frost 1996, White 1983). Also a number of other tree species are frequently encountered alongside the dominant ones. Species of *Uapaca* are often even featured as dominants on shallow soils and secondary forest areas of miombo (White 1983).

Figure 2. A sole *Brachystegia sp.* by the border of a cleared miombo stand, photographed close to the community of Ligogolo in Muembe district, Niassa province, Mozambique. Photo: Arttu Pienimäki.

Structure and fire dynamics

Various studies conducted in Tanzania recorded a clear reverse J shaped diameter breast height (DBH) distribution on miombo woodlands, repeatedly across all measurement sites (Kashindye et al. 2013; Shirima et al. 2011; Isango 2007; Backéus et al. 2006). A generally small proportion of the trees measured in these studies exceeded DBH of 50 cm. The few largest individuals though had a DBH of 70–80 cm, or even 90 cm (Backéus et al. 2006). Ribeiro et al. (2013) derived similar results from Niassa Reserve in northern Mozambique, excluding the presence of remarkably large trees. They found 69 % of the individual trees belonging to the DBH group of 5–15 cm, while trees with a DBH of over 45 cm accounted for only 0.55 % of the stem count. The results demonstrate presence of a wide tree size distribution on miombo woodlands, as typical for savanna-like ecosystems. The tree diameter growth mainly takes place during the rainy season (Elifuraha 2008).

The stem densities reported for miombo vary widely, since the figures related to J shaped DBH distributions are sensitive to the minimum definition of a tree (height and DBH requirements). Shirima et al. (2011) had a relatively high minimum definition of 10 cm DBH, which resulted in densities of 281–382 stems per hectare. This gives an idea about the density of larger trees on miombo. A better overall density estimator is basal area (BA). Frost (1996) suggests that most of the mature miombo woodland stands have a BA ranging between 7–19 m^2 ha^{-1}, which is supported e.g. by results from Kalaba et al. (2013b), Shirima et al. (2011) and Backéus et al. (2006). Lower minimum BA values have been recorded as well (e.g. Williams et al. 2008), but Backéus et al. (2006) note that their occurrence is most typically related to wood harvesting by humans.

Trees of miombo woodland demonstrate a relatively limited height. Stands generally achieve a dominant height of 10–20 m (White 1983). Heights over 15 m are reached on wetter miombo, while heights on drier miombo remain under 15 m (Frost 1996). Certain species of *Brachystegia* have been recorded to reach a height of 30 m, however under special conditions with the sites probably representing a vegetation type more productive than miombo (White 1983).

Shrub layer and herbaceous vegetation layer demonstrate a wide variety of structural compositions on miombo, the former being typically discontinuous and the latter being continuous under the trees but varying in density (Campbell et al. 1996; Frost et al. 1996). The composition of herbaceous vegetation is greatly affected by fire among other things (Furley et al. 2008).

It is shown by Sankaran et al. (2005) that African savanna ecosystems receiving annual precipitation of 650 mm or more have a potential to develop into closed canopy stands, unless the tree cover is reduced by disturbances. The precipitation figure applies to miombo woodlands exactly. Indeed, at least two major natural disturbance factors are recognized on miombo: fire and elephants (Ribeiro et al. 2008b; Mapaure & Campbell 2002; Frost 1996).

Where elephants are nowadays widely suppressed to nature reserves, fire is considered as a fixed feature of the miombo landscape (Campbell et al. 1996). It is also evident that the present day fire intensity on miombo region is significantly increased due fires of anthropogenic origin (Ryan & Williams 2011; Timberlake et al. 2010). Burning experiments have showed that the species diversity on miombo is barely influenced by fire occurrence at least on short terms, indicating adaptation in the evolutionary traits of the plants (Furley et al. 2008). However, significant effects on vegetation and stand structure have been recorded. These occur as biomass removal and tree kill by fire, with especially high kill rates on small trees (Ryan & Williams 2011; Furley et al. 2008).

1.1.2 Carbon stocks of miombo landscape

The global context

Dixon et al. (1994) have estimated the contribution of forest ecosystems to the global carbon pool. According to them, the forests of the world carry a total of about 1150 Pg of carbon, stored in vegetation and soils. It is further estimated in their study that 10 % of the global total stock and 15 % of the vegetation stock alone are situated in Africa. Gaston et al. (1998) present a more detailed forest carbon stock distribution exclusively for Africa. They estimate total forest, savanna and grassland C stocks for each of the African countries. Given the complexity of fitting miombo woodlands in any of those three classes by definition, the total figure for miombo woodlands alone is not calculable. However, the total C stock sum of five countries with a major miombo cover (Angola, Mozambique, Tanzania, Zambia and Zimbabwe; Figure 1) is circa 4.7 Pg. How much miombo accounts for this total figure remains without proper estimate, but since some of these countries also include tropical evergreen forests (White 1983) with generally higher C stock density than miombo (Lewis et al. 2009), a conservative approach should be applied.

Presented estimates for carbon stocks aboveground

It is mainly the wide distribution of miombo woodlands rather than the vegetation carbon stock density that makes miombo woodlands significant in the global carbon cycle. Various site-specific estimates of miombo C stocks per area unit have been made prior to this study. The most studied C sub-stock on miombo is arguably vegetation aboveground carbon, with trees representing the most significant component. It is typically estimated by applying allometric equations based on narrow destructive sampling to wider inventory data.

Frost (1996) demonstrates a positive correlation between mean annual rainfall and aboveground biomass (BM) of miombo. His aboveground BM suggestion for drier miombo woodlands and wetter miombo woodlands is 55 Mg ha^{-1} and 90 Mg ha^{-1} respectively. Assuming C content of 0.47 for BM (IPCC 2006), the figures respectively stand for 26 Mg ha^{-1} and 42 Mg ha^{-1} in terms of carbon.

A group of more recent studies that mostly measured relatively undisturbed miombo woodlands provide estimates of comparable magnitude for the aboveground C stocks. They are presented in Table 1. Also an older estimate by Chidumayo (1990) is included. Notably many of the mean stocks provided remain lower than the averages estimated by Frost (1996).

Timberlake et al. (2010) modeled tree aboveground biomass for Zambezian woodland (miombo) based on a wide set of BA results. Their estimate is 88–97 Mg ha^{-1}, which converts into 41–46 Mg ha^{-1} in terms of carbon (IPCC 2006). These figures again are notably higher than majority of the ones presented in Table 1. On the other hand, some single observations from those have very high values. This speaks for spatial heterogeneity in C stocks of miombo woodlands. The wide distribution of results may reflect the difference between wetter miombo and drier miombo as suggested by Frost (1996), or presence of sample plots with miombo degradation by natural or anthropogenic factors.

It is not uncommon that miombo stands are degraded to some extent by the factors mentioned above. It is important to notice that these degraded forests represent an increasing share of the miombo woodlands (Dewees et al. 2011), and that various studies include measurements on them. For example the study by Williams et al. (2008) addressed C stocks on a number of re-growing plots of secondary miombo in addition to C stocks on a protection area (figures given in Table 1 considering the latter). The mean aboveground C stocks in these cases have generally lower values than undisturbed miombo.

Table 1. Carbon stocks recorded for miombo woodlands according to other studies. All figures are given as Mg ha^{-1}. Only the C stock of woody vegetation, primarily trees, is included. * Figures converted from biomass assuming C content of 0.47 (IPCC 2006).

Mean	**S.D.**	**Min**	**Max**	**Study site**	**Reference**
19.0	8.0	4.3	33.4	Mozambique; Sofala province	Williams et al. 2008
20.5	3.3			Tanzania	Chamshama et al. 2004*
21.2	1.4	1.9	60.9	Mozambique; Sofala province	Ryan et al. 2011
21.7		8.4	42.2	Mozambique; Sofala province	Woollen et al. 2012
22.0	4.6	16.9	30.7	Mozambique; Sofala province	Ryan & Williams 2011
23.3	9.8	13.5	29.8	Tanzania	Shirima et al. 2011
26.48	9.38			Mozambique; Manica province	Sitoe et al. 2009
29.88	13.07	10.0	79.7	Mozambique; Niassa province	Ribeiro et al. 2013
37.2	1.3			Tanzania	Kashindye et al. 2013*
39.6	1.5	28.7	52.8	Zambia	Kalaba et al. 2013b
41.9	6.4			Zambia	Chidumayo, 1990*

Ribeiro et al. (2008a) approached the matter by dividing miombo into categories defined by tree crown cover in their study based on remote sensing data from Niassa Reserve, Mozambique. The study area is known to include loss of trees caused by anthropogenic fires and herds of elephants (Ribeiro et al. 2008b). The group resulted in three different miombo classes with respective C stocks as follows: high density woodlands 35 Mg ha^{-1}, medium density woodlands 19.5 Mg ha^{-1} and low density woodlands 10.5 Mg ha^{-1}.

The other aboveground C sub-stocks on miombo, alive or dead, have not been studied to equal extent but their contribution to the total C stock is evidently also very limited. Herbaceous vegetation generally makes up 2–5 % of the total aboveground BM (Frost 1996). For the respective C stock, values ranging between 0.5–2.0 Mg ha^{-1} have been reported (Ribeiro et al. 2013; Woollen et al. 2012; Shirima et al. 2011; Sitoe et al. 2009; Chidumayo & Kwibisa 2003). Litterfall has been measured to add 0–2 Mg ha^{-1} to the total C stock (Ribeiro et al. 2013; Woollen et al. 2012; Frost 1996).

When it comes to dead wood C stocks, only two estimates were found. One (Sitoe et al. 2009) valued circa 0.7 Mg ha^{-1} while the other (Ribeiro et al. 2013) valued so close to zero that it was practically negligible. Yet there are factors with potential of producing dead wood on miombo. Fire is common, and the most intense fires are recorded to be able to kill up to 12 % of the stem count of a miombo stand (Ryan & Williams 2011). Ribeiro et al. (2008b) and Mapaure & Campbell (2002) measured notable stand damages by elephants in addition to fire. However, these kinds of factors are highly local instead of being distributed evenly across the miombo.

The total aboveground C stocks on miombo woodlands remain modest compared to correspondent figures measured from tropical evergreen forests of Africa, which average about 200 Mg ha^{-1} (Lewis et al. 2009). However, there is evidence that the largest C stock on miombo by far is comprised by soil organic carbon (SOC) rather than the living vegetation (e.g. Ryan et al. 2011; Walker & Desanker 2004).

Presented estimates for carbon stocks belowground

Methods for estimating vegetation belowground BM are neither well established nor standardized, since they present a challenging process for researchers (Pearson et al. 2005; IPCC 2003). This results in that much less is generally known about the vegetation BM belowground component than the aboveground component.

There is an apparent shortage of studies including root excavation in miombo woodlands. One such study conducted in Tanzania (Malimbwi et al. 1994) resulted in root BM comprising 20 % of the total woody BM. Two recent studies that were conducted in Zambia (Chidumayo 2013a) and Mozambique (Ryan et al. 2011) and included root excavation resulted in higher figures of 35 % and 33 % respectively. This matches a recapitulation by Frost (1996) that suggests belowground BM share ranging between 32–37 % of the total woody BM. Mokany et al. (2006) have conducted a comprehensive meta-analysis of root to shoot (R:S) ratio studies globally. They suggest a R:S ratio of 0.322 for tropical dry woodlands, which stands for circa 24 % of the vegetation total biomass.

Soil organic carbon represents the last major C sub-stock of miombo woodlands, and possibly the one with most significance in global carbon cycle. Available studies are limited, but they indicate a C stock either equal to or larger than the vegetation altogether. Ryan et al. (2011) and Walker & Desanker (2004) measured SOC stocks of 76.3 and 79.6 Mg ha^{-1} down to 0.5 and 1.5 m respectively. Both studies addressed multiple, fixed depth layers of soil. The results of the former demonstrated a clear exponential decay of SOC content with increasing depth along the whole sampling profile, and the results of the latter recorded SOC content decrease until the depth of 15 cm after which it remained relatively constant. Rossi et al. (2009) measured a SOC stock of 72.47 Mg ha^{-1} from 1.0 m deep soil pits, though the sampling size was limited. Notably, all three results are very close to each other, even though there is a wide variation in the sampling depths. Part of this is explained by the exponential decay of the C content, but the results also speak for differences between study sites.

Two studies that addressed only the top 30 cm of the soil (referred to as topsoil throughout this study) in miombo were found. Woollen et al. (2012) resulted in an average SOC stock of 40.1 Mg ha^{-1}, with the top 5 cm accounting for circa 30 % of the whole stock of the 30 cm layer. Williams et al. (2008) do not provide their SOC stock mean value, but report a median of 57.9 Mg ha^{-1} instead.

1.1.3 Land use conversion and miombo socioeconomic role

The present human footprint on miombo landscape is a result of a long continuum. Evidence from southwest Tanzania indicates that the local miombo landscape has been affected by wide-scale fires for at least 1500 years, coinciding with the arrival of agriculturist people to the area and hence being presumably anthropogenic (Thevenon et al. 2003). While it is evident that the co-existence of miombo woodlands and people does not take place without any disturbance on ecosystem, the critical issue from the ecosystem point of view is the disturbance intensity. Generally, severity of deforestation and forest degradation has followed the human population growth on miombo region, and hence accelerated (Misana et al. 1996).

Two decades ago Hannah et al. (1994) estimated that 62 % of the miombo ecoregion still remained undisturbed, while the rest fell under categories “partially disturbed” and “human dominated” (21 % and 17 % respectively). Also the population densities on much of the miombo region were relatively low for the time being (Campbell et al. 1996). Nowadays, at least 100 million people either inhabit the miombo region or stand otherwise straight dependent of it considering their livelihoods (Dewees et al. 2011), and given the population growth rates of sub-Saharan Africa, the figure is likely to increase exponentially in the future. While parts of the miombo woodlands still exist relatively intact, rapid processes of deforestation and forest degradation are widely ongoing (Dewees et al. 2011; Abdallah & Monela 2007) (Figure 3).

For local people, miombo woodlands provide both wood products like fuelwood and construction material, and non-wood forest products (NWFPs) like food, medicines and fodder (Clarke et al. 1996). Also ecosystem services such as erosion control, water regulation and soil fertility promotion are provided (Clarke et al. 1996). A study by Kalaba et al. (2013a) revealed that forest products from miombo constituted circa 44 % of the income of an average rural household in Copperbelt of Zambia. The share was even greater among the poorest of the households.

While forest product harvesting can still be seen as relatively harmless, a way more destructive phenomenon is the expanding agriculture traditionally practiced as shifting cultivation widely across the miombo region (Frost 1996). Jansen et al. (2008) discovered in their Mozambique-based study addressing land use change dynamics, that miombo woodlands decreased substantially during the survey period of 1990–2004 while being replaced by agricultural land. They also discovered that agriculture is changing towards practices more permanent than shifting cultivation, which again processes greater barrier for miombo regeneration. Also timber harvesting – both legal and illegal – has been blamed for causing deforestation and forest degradation in this context. Even though miombo houses valuable species to a very limited extent, selective logging does occur, and it opens the way to the woodlands for the other actors to exploit (Sitoe et al. 2012).

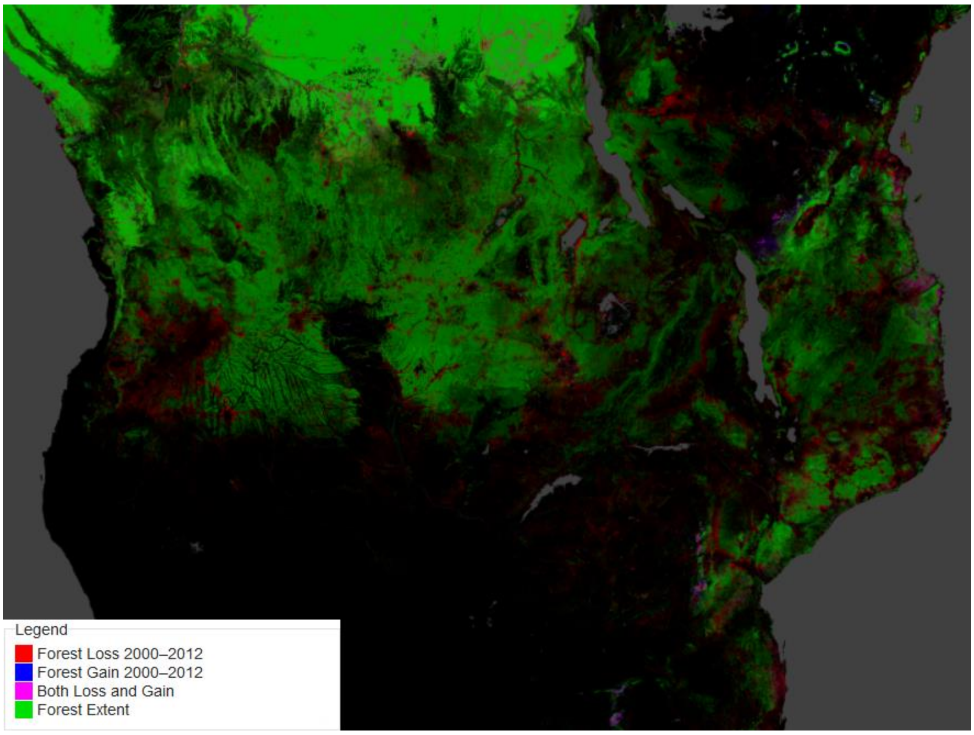

Figure 3. Forest cover and forest cover change in the miombo region in 2000–2012. Source: Global Forest Change map by Hansen et al. (2013); map interface by Google Earth. Available online: [http://www.earthenginepartners.appspot.com/science-2013-global-forest]

Another key driver promoting woody biomass loss in the miombo region is the demand for fuelwood and charcoal, which together account for about 70 % of the energy consumed in southern Africa (Syampungani et al. 2009). The production of charcoal especially is increasing with the rapid population growth (Syampungani et al. 2009) and the lack of alternative energy sources (Sitoe et al. 2012; Kutsch et al. 2011). The pressure on forests and woodlands due to charcoal production is greatest in proximity of urban areas (Sitoe et al. 2012), and zones of deforestation have developed around major human settlements (Kutsch et al. 2011).

Chidumayo & Gumbo (2013) state that charcoal production cannot be held as the sole reason for deforestation, since the activity only leads into forest degradation on the landscape level. This indicates a more complex pattern of land use change, where one activity makes way for the other. The argument is supported by evidence of miombo ecosystem appearing relatively resilient, when given time to recover. Chidumayo (2013b, 2004) found strong regeneration of miombo following clear cut, which occurred through resprouting of the preceding woody vegetation. Williams et al. (2008) monitored re-growth of abandoned agricultural lands, and found no difference neither in terms of carbon stocks nor biodiversity indices between undisturbed woodlands and sites with about 25 years of abandonment. It appears that suppressing miombo down to degraded fallow requires constant land use pressure by human activities.

As a synthesis, the land covers replacing miombo woodlands are of anthropogenic origin, and generally either active agricultural land or transitional vegetation of some kind. Third possibility is forest plantations of exotic species, further addressed in the chapter below.

1.1.4 Forest plantation investments in Mozambique

The forest industry sector has undergone a global change, in which the production is shifting from the natural forests of Europe and North America increasingly to intensively managed forest plantations in Asia, Africa and Latin America (Toppinen et al. 2010; Bael & Sedjo 2006). The shifting is catalyzed by faster growth of wood and cheaper factors of production in these areas (Bael & Sedjo 2006), out of which land is the most important (Toppinen et al. 2010).

Forest plantations typically consist of intensively managed stands of exotic species intended to produce wood or non-wood forest products (FAO 2006). The most common forest plantation species are eucalypts and southern pines, with the former mostly grown for pulpwood and the latter grown for timber (Evans & Turnbull 2004).

Mozambique is a country with relatively high remaining forest cover, but fast rates of deforestation and forest degradation (Sitoe et al. 2012; Marzoli 2007). The forest loss has lead into availability of cleared land for companies to pursue, and recently several large scale plantation forest investments have occurred or are currently occurring in the country (Nhantumbo et al. 2013). Industrial forest plantation projects are also inviting from the government point of view, providing much-desired foreign investments. The Mozambican state has identified 7 million ha of potential land for industrial forest plantations in the country (mainly located in the northern part), out of which 3 million ha are already targeted for practical land allocation for this purpose (República de Mozambique 2013).

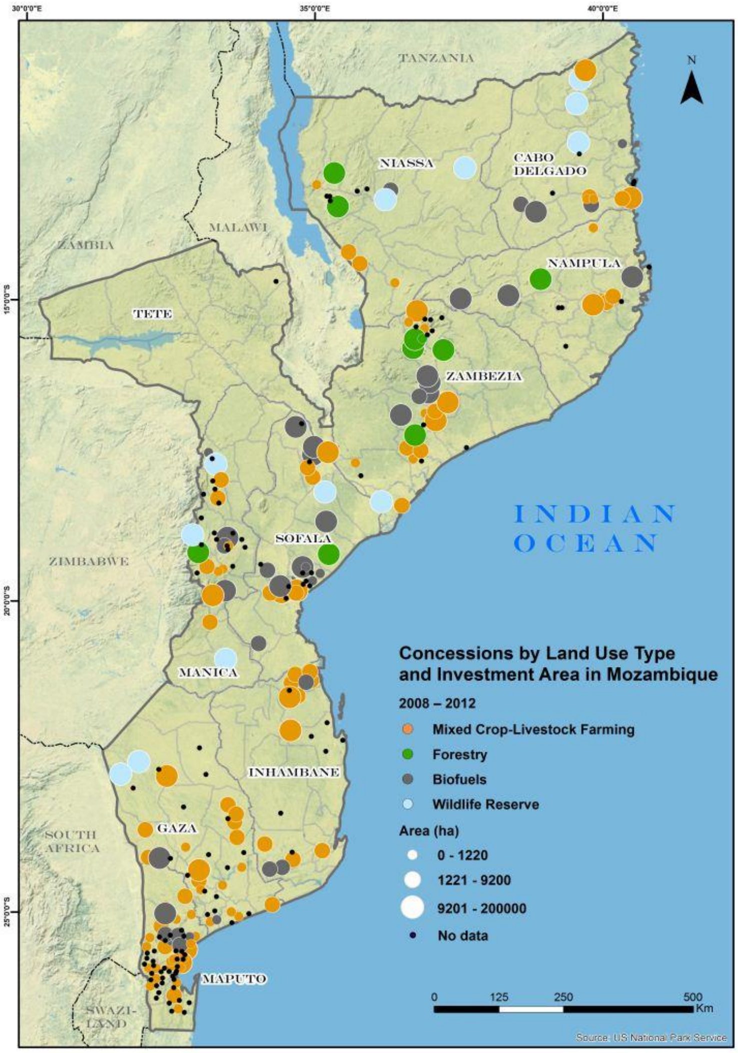

Figure 4. Concessions for agricultural and forestry investments in Mozambique by area and type. Source: PAIMO project work package 1.

Figures about the existing forest plantation cover have been few and outdated. Marzoli (2007) estimated that planted tree stands in Mozambique covered about 1.7 million hectares, however only undefined part of the figure representing industrial pulp and timber plantations. FAO country report for Mozambique, in contradiction, estimated that the total area of forest plantations in 2005 had been a modest 24000 hectares (FAO 2010). Most recently, the PAIMO project (see section 1.1.5) mapped forestry investments in Mozambique based on the official concessions allotted to the purpose by the government (Figure 4). Since no private land ownership is recognized in Mozambique, land use concessions granted for 50 years are the primary way in which forest plantation companies can obtain land (Sitoe et al. 2012).

Industrial forest plantations are a relatively new phenomenon in Mozambique, and their effect on both livelihoods of the local people and carbon stocks of the ecosystem on a miombo landscape are still poorly known. It has been recognized that the introduction of plantations will cause major land use changes, which again are going to impact the rural communities (Landry & Chirwa, 2011).

1.1.5 PAIMO project framework

This study has been conducted in the framework set by an academic research project titled PAIMO. The project was established to address the need of evaluating diversified industrial plantation establishment effects in southern African context – the initials stand for Private Agricultural Investments and Land Use Change Impact on The Adaptive Capacity of Local Communities to Climate Change in Mozambique. The main focus of the project has been on forest plantation investments, in which sense the title may appear deceptive. Arguably the most significant group of any private LULUCF sector investments in the selected study area of northern Mozambique is currently formed by forest plantations.

PAIMO project has been carried out jointly by Viikki Tropical Resources Institute (VITRI) at University of Helsinki and Pellervo Economic Research (PTT), both based in Helsinki, Finland, and Eduardo Mondlane University (UEM) based in Maputo, Mozambique.

PAIMO project has four diversified work packages, each addressing the industrial plantation investment scenario from a different aspect. Work package 1 maps the existing plantation investments and compares them by numbers. Work packages 2 and 3 have their focus on plantation investment socioeconomic effects on local communities, with interviews of the local community members as the main study method. Work package 4 estimates the effects of plantation investments on carbon stocks of the landscape.

1.2 Objectives of the study

The outcomes of this master's thesis study are intended to provide the information required for executing the PAIMO work package 4. The objectives are listed below:

General objective	Compare carbon stocks (Mg ha^{-1}) between native vegetation and forest plantations on the study site.
Specific objectives	
Objective 1	Quantify carbon sub-stocks and calculate the total average carbon stock on different types of native vegetation.
Objective 2	Quantify carbon sub-stocks and calculate the total average carbon stock on different types of forest plantations.

The correspondent research questions are:

Research question 1	How large are the average carbon stocks of the land use types representing native vegetation?
Research question 2	How large are the average carbon stocks of the land use types representing forest plantations?

Hypotheses of the study:

H0: Forest plantation establishment has no effect on the carbon stocks.

H1: Forest plantation establishment has an effect on the carbon stocks.

2. MATERIAL AND METHODS

2.1 Study site

The study was conducted in the province of Niassa in northern Mozambique. The province is located in the northern part of the country by Lake Malawi and the border of Tanzania (Figure 5). Niassa has the lowest population density in Mozambique, with majority of people inhabiting rural areas and being dependent of subsistence agriculture and surrounding nature (Nhantumbo et al. 2013). The vast majority of the province belongs to the miombo region (White 1983).

The total area of Niassa covers 12.9 million ha, and as for the forest plantations, 2.47 million ha have been identified as potential for them and 0.64 million hectares are in the process of land allocation to plantation companies (Nhantumbo et al. 2013).

Figure 5. Location of the study site. Source of the maps: Google Maps (AfriGIS 2014) and Bing Maps (Nokia 2013; Earthstar Geographics SIO).

The field sampling areas of the study were located in the districts of Lichinga, Sanga and Muembe, east and northeast from the provincial capital city Lichinga (Figures 5 and 7). The distance from Lichinga to the sampling areas ranged between 5–60 km.

One sampling area was located about 10 km south of the city. The study site as a whole included forest plantation activities by several private forestry companies, mosaics of traditional land use including slash-and-burn cultivation, as well as native miombo woodlands affected by varying level of human influence.

The mean annual rainfall is reported varying mainly between 1000–1400 mm in the three districts housing the study site, though the areas of the highest altitudes even receive more (Ministério da Administração Estatal, 2005a, 2005b, 2005c). White (1983) categorizes the study site as wetter miombo, which is supported by the high mean rainfall figures. The altitudes are generally high, ranging on both sides of 1000 m, which causes high variation of temperature between the seasons (15–35°C with the annual mean generally less than 22°C) (Ministério da Administração Estatal, 2005a, 2005b, 2005c). Soils of the area are most typically fine-textured red clay soils (Ministério da Administração Estatal, 2005a, 2005b, 2005c).

The field measurements of this study took place on the study site during September and October 2010.

2.2 Methodological framework

This study required adopting a locally relevant land use classification, including the forest plantations, in order to provide a basis for a detailed carbon stock comparison. Once classification was determined, it acted as a basis for stratification, followed by field sampling of each land use class (LUC). Carbon stocks were then quantified with calculations based on the results of the field survey.

The total carbon stocks were calculated as a sum of three major carbon sub-stocks (Table 2): aboveground vegetation, belowground vegetation and soil organic carbon (SOC). This division was applied on all LUCs of the study. Each of the included C sub-stocks carried a separate methodology of quantification. Litter and dead wood as sub-stocks were excluded from the survey. This was because of their presumably limited contribution to the total C stocks and because of the limited time and resources of the study as well. The final decision was made on field, based on visual estimation of their low quantities.

Table 2. The list of carbon sub-stocks included in the scope of this study.

Carbon sub-stock	**n (cumulative)**
Vegetation aboveground carbon	1
Trees	2
Shrubs and saplings	3
Herbaceous vegetation	4
Vegetation belowground carbon	5
Soil organic carbon	6

Aboveground vegetation carbon was further divided into three subcategories in the measurements. Carbon stock of trees was estimated based on allometric equations, whereas carbon stocks of shrubs and saplings as well as the herbaceous vegetation were measured with methods of destructive sampling. Belowground vegetation carbon was estimated solely based on allometric equations due practical limitations of the field work. Soil organic carbon was determined in laboratory from soil samples collected in the field.

Prior to measurements, the forest plantations of the study area were known to be extensively juvenile and not represent the average of the intended growing schemes for the time being, concerning vegetation carbon stocks both above- and belowground. On the contrary, it was assumed that vegetation carbon stocks of other land uses had reached an equilibrium state. Their average carbon stocks were assumed to be recordable directly by repeated measurements on sampling plots, as long as the natural variation of the class would be equally covered. This difference in maturity between the land uses placed requirements for the methodological design of the study.

The resulted approach was to divide land use classes into two main groups: *native vegetation* and *forest plantations*. The methodological framework, demonstrating the differences between the groups, is illustrated in Figure 6. Most importantly, an extra step of estimating the plantation growth was included in the methodology concerning the forest plantations group. This was done based on field measurement results, existing growth models and growing schemes provided by the plantation owner. The other methodological differences between the two groups included a different sampling strategy, further described in chapter 2.4, and some technical modifications in field measurements.

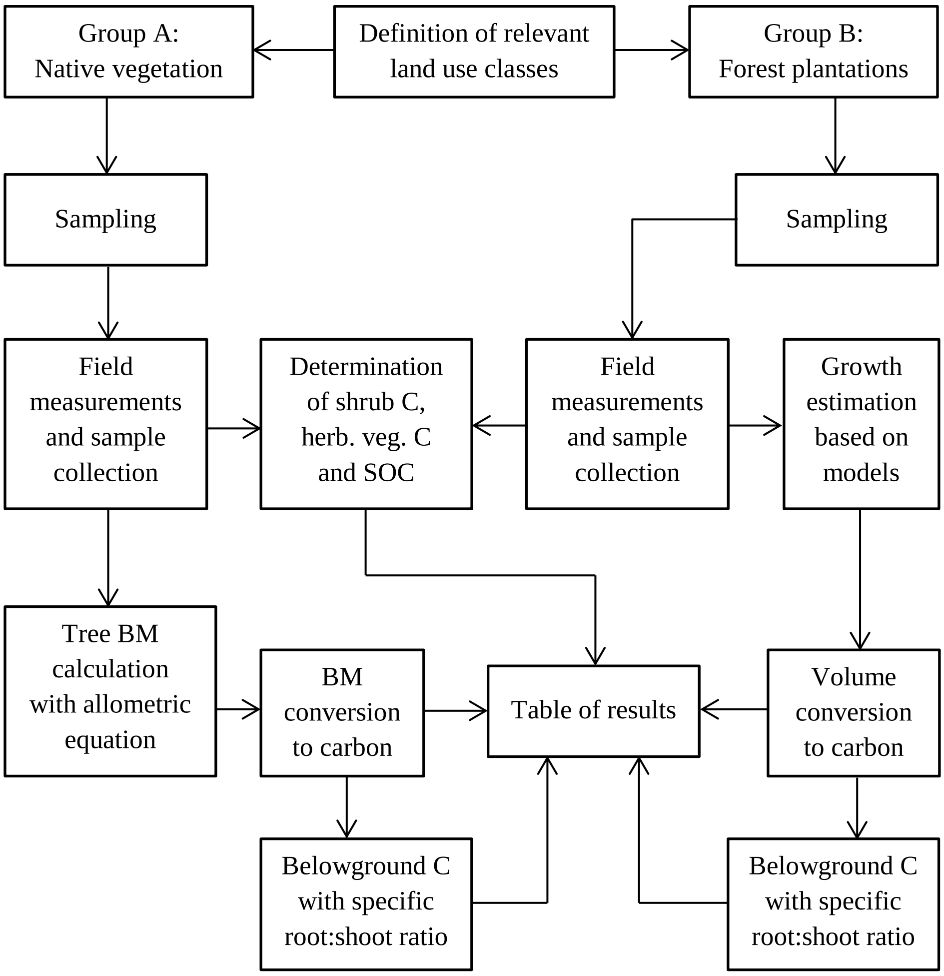

Figure 6. The methodological framework of this study.

2.3 Land use classes

2.3.1 Classification process

Determination of the LUCs to be used in this study started by evaluating the relevance of existing classifications, in relation to the objectives of the study and the landscape of the study site. Discovered existing classifications had been formulated in past forest inventories concerning this part of Africa and also in the UEM research tradition concerning comparable studies. The landscape of the study site was addressed with literature and aerial photos, and later with field visits as well.

The final land use classification adopted in this study is strongly influenced by the UEM research tradition, and has its basis on on the classification adopted by the second and the newest national forest inventory (Inventário Florestal National, IFN) completed in Mozambique (Marzoli 2007). The IFN classification recognises FAO's definition of forest. This system was chosen since it was considered to be of highest relevance and applicability. The vast majority of IFN classes were dropped out herein since they were too detailed for, or fell outside of the interest area of this study. On the contrary, the single class of forest plantations in IFN was divided into two classes: eucalypt and pine plantations. These were the two major planted tree genera present on the study site.

The only type of pristine natural vegetation discovered at the study site was miombo, presumably the dominant land cover before the presence of major human influence (White 1983). Human activities as disturbance, most typically constant removal of wood for charcoal production or clearance of new farmland, had caused appearance of the other land covers that lacked the defining characteristics of miombo. Plantations formed a new type of land cover emerging from anthropogenic origin.

A major land cover that was excluded from the study was active farmland, consisting of small-scale household farms called *machambas*. Since the field work was carried out during dry season, farmland represented practically bare soil with low overall relevance to perform biomass measurements on. Instead, abandoned fallow land of the past farms was included as a LUC.

Six distinctive LUCs were finally chosen to be included in the survey, four of them representing native vegetation and two of them representing forest plantations. This classification was considered to be both comprehensive and continuous in relation to the land cover present on the study site, as well as relevant in relation to the study objectives. The adopted classification is presented in Table 3, followed by a brief description of each class. Ground photos depicting the six classes are included in Annex 1.

Table 3. The land use classification applied in this study.

Land use class	**Label**	**Classification criteria**	**Group**
Dense miombo	MDe	Native forest; canopy cover above 40 %	Native vegetation
Open miombo	MOp	Native forest; canopy cover below 40 %	
Other woody vegetation	OWV	Woodland degraded below the FAO definition of forest OR former agricultural land with 5 or more years of abandonment	
Fallow land	FaL	Former agricultural land with less than 5 years of abandonment	
Eucalypt plantations	EuP	Industrial plantations consisting of *Eucalyptus sp.*	Forest plantations
Pine plantations	PiP	Industrial plantations consisting of *Pinus sp.*	

2.3.2 Description of the classes

Dense miombo

Dense miombo was the first of the two native vegetation land use classes in this study that were considered to be forest according to the FAO definition, which requires canopy cover above 10 % and minimum height of 5 meters (FAO 2010). In order to be classified as dense miombo, a woodland stand had to exceed both the minimum height and a canopy cover of 40 %. The latter was the distinctive factor between this class and open miombo.

Dense Miombo represented the relatively undisturbed native woodland in the landscape of the study site. It only appeared on more remote areas of the study site, uneasily reachable or far away from major human settlements.

Open miombo

Open miombo was the second native vegetation land use class to meet the FAO (2010) forest definition. Like on dense miombo the dominant height on open miombo was above 5 meters. Canopy coverage had to meet the FAO minimum requirement of 10 % (FAO 2010), but remain under 40 % on the contrary to dense miombo.

Open miombo represented native woodland like dense miombo, but typically carried moderate signs of forest degradation at the study site, indicating that human activities were the major cause of lower canopy coverage. However, in some cases the lower canopy coverage appeared to be a result of site characteristics rather than human activity.

Other woody vegetation

Areas dominated by trees or shrubs but not falling under the FAO definition of forest were classified as other woody vegetation. In addition, if the site had been under agricultural use before, more than five years of abandonment were required as a classification criterion.

Other woody vegetation represented a heterogenic group of degraded miombo vegetation. The areas representing other woody vegetation carried heavy signs of continuous forest degradation with major removal of woody biomass. This class appeared widely alongside fallow land in proximity of human settlements. The other woody vegetation LUC practically always appeared to be a result of human activity at the study site. Except of very marginal areas such as rocky formations, actual native shrublands or grasslands were not encountered.

Fallow land

Abandoned agricultural areas (machambas no longer under active management) were included in the study as the fallow land class. Preceding abandonment period with a maximum of five years was required as a classification criterion. After five years of re-growth, the abandoned machambas would typically fall into the class of other woody vegetation already.

Fallow land was dominated by herbaceous vegetation accompanied by shrubs and young trees to varying extent. Aside from active machambas, fallow land was typically the dominant land use appearing in conjunction with human settlements. Also heavily degraded grasslands and shrublands with no apparent history of agriculture as previous land use can be held as a part of this class. However, no plots of this kind were measured in the course of this study.

Eucalypt plantations

The first of two forest plantation classes, this class covers homogenous stands of industrial tree plantations consisting of eucalypts. The species included in the survey were *Eucalyptus grandis* and *Eucalyptus urograndis* (hybrid species *E. grandis* x *E. urophylla*), which were the primary species presently planted on the study site. Since the state of the forest plantation industry on the study site is still in an early stage, the vast majority of the eucalypt stands present were juvenile. An intense soil preparation reaching down to 80 cm had preceded the recent plantings, necessary to break the extremely hard structure of the clay-rich soil for roots to grow.

Pine plantations

Highly similar in other characteristics with eucalypt plantations except the species, this class covers the industrial tree plantations consisting of pines. The species included in the survey were *Pinus patula* and *Pinus maximinoi*. The latter was planted widely on the study site at the time of the field work as an industrially newly emerged species, and the former was included to get observations of older-growth stands generally formed by this species on the study site. However, no truly late-rotation stands were present on the study site for time being.

2.4 Sampling

2.4.1 Principles of the sampling

The requirement for the sampling system was to get a sufficient number of observations per land use class, so that the statistical validity of the data would be ensured. Further requirements included the system to be as efficient and objective as possible. In the complex multi-level mosaic of land uses distributed over the study site, applying an objective sampling system with the study objectives and given resources presented a challenge. Eventually, it was decided to apply subjective sampling for choosing the microsites for field measurements (further referred as measurement areas or field measurement areas) on the study site. A sampling grid was then placed on each of these field measurement areas. This was done with a random starting point to ensure objective placement of the sample plots on the level of field measurement areas.

The criteria for choosing the field measurement areas were (i) presence of the LUC characteristics presented in chapter 2.3 (ii) dominance of a single LUC on area (iii) area size sufficient to theoretically house about twenty or more sample plots (iv) proximity to community included in the PAIMO project socioeconomic survey. The last criterion had to be considered both from the logistic point of view and to ensure the data validity in the whole PAIMO project framework. Extensive scouting in the field, aerial photo consultancy on Google Earth and Bing imagery, and stand information on forest plantations were all applied in the choosing process. A detailed description of the field measurement areas that were measured in this study is presented in chapter 2.4.3.

Soil sampling was fixed as a part of the plot design, so systematic sampling strategy also applied with the soil sampling. Soil sampling aimed at getting a high number of samples for C content determination, since the variation could neither be predicted nor calculated in course of the study. In order to make the soil sampling more efficient, composite sampling was applied in the process. Composite sampling reduces both the number of samples to be analyzed and the variation between them while maintaining the coverage of the sampling high (Mason 1992).

2.4.2 Applied sampling protocols

The following protocol applied for native vegetation LUCs. Each LUC was measured primarily on a single field measurement area. Any plots falling outside of the LUC in question were excluded from the sampling. Coordinates for the starting point were derived randomly from Google Earth and a grid with plot interval of 100 meters was applied. Tentative results for aboveground tree and shrub carbon stocks were calculated along the survey. A generic allometric equation developed for Mozambique (derived from Henry et al. 2011) and an estimated coefficient of 0.25 for fresh biomass carbon content were used in the process. The tentative results were applied into MS-Excel based Winrock Sampling Calculator (Walker et al. 2007) to calculate the minimum theoretical sampling intensity per LUC. This enabled adjusting the sampling intensity during the field survey, and ensured that the final sampling intensities of the study remained well above statistically safe numbers.

Forest plantation LUCs on the contrary were sampled with homogenous plantation stands as field measurement areas. The stands included in the study were hand-picked based on stand information provided by the plantation owner. The information included species, age, stem count and survival rate, but there was no growth or yield data available. The aim of the sampling was to include as many age cohorts of the surveyed species as possible with two or more replicate plots on each stand. The number of sample plots per plantation stand was kept low since the stands were expected to be relatively homogenous each. A stand was not chosen if it had demonstrated low survival rate according to the pre-information.

A grid with a plot interval of 50 meters was applied on the forest plantations due to limited stand sizes and smaller plot radius compared to native vegetation. A starting point for each grid was chosen randomly in the field. It was not possible to calculate tentative results along the survey of the forest plantations, because the methodology of the study required growth estimation in the calculations phase. A number of plots comparable with the other LUCs was measured both on eucalypt and pine plantations.

2.4.3 Field measurement areas

General figures

A total of 93 sample plots were surveyed in this study, with 59 of them placed on native vegetation LUCs and 34 on forest plantation LUCs. The detailed distribution is shown in Table 4.

Table 4. The number of measured sampling plots per each land use class.

Land use class	**n of sample plots**
Dense miombo	13
Open miombo	16
Other woody vegetation	17
Fallow land	13
Eucalypt plantations	15
Pine plantations	19
Total	93

Native vegetation was sampled on four primary areas, coded A, B, C and D (Figure 7). They were used to survey a single class each. One more area, coded F, was measured as an additional site. Plots of both open miombo and other woody vegetation were surveyed on area F. The total number of sample plots measured per a native vegetation LUC varied between 13 and 17. Each of the grids on areas A–F ended up having missing observations, because points representing wrong LUC or falling on some completely different land cover, like road, were excluded.

There was a higher number of forest plantation field measurement areas (stands) than those of native vegetation (Figure 7). This was because of the different sampling protocol. The number of sample plots measured per stand varied between 2 and 5.

Altogether, 5 different eucalypt stands 6 different pine stands were sampled and measured, housing a total of 15 and 19 sample plots respectively.

Figure 7. Location of the field measurement areas of this study. Red markers point the native vegetation areas A to F. Blue unlabeled markers point the measured forest plantation stands. Also the locations of the city of Lichinga and communities of Chimbonila, Muembe and Malulu are marked. Map compiled with Google Earth.

Area A

Fallow land LUC plots were measured at area A. The area was located about 20 kilometers east from the city of Lichinga, on the southern side of the highway leading from Lichinga to Marrupa. The distance to the community of Chimbonila – an administrative center and a settlement of notable size in terms of Niassa province – located on the western side of the measurement area was only 2 kilometers. A tiny roadside community neighbored the measurement area in northeast. The exact location and sample plot composition of area A is shown in Figure 8.

A total of 20 plots were visited at area A, seven of which were in active agricultural use at the time of the measurements and were hence excluded from the study. Measurements were conducted on 13 plots. Two plots were shifted towards the correct LUC (see 2.5.2 for point shifting). Since area A was the sole area for fallow land LUC measurements, a total of 13 fallow land sample plots were eventually recorded in the study.

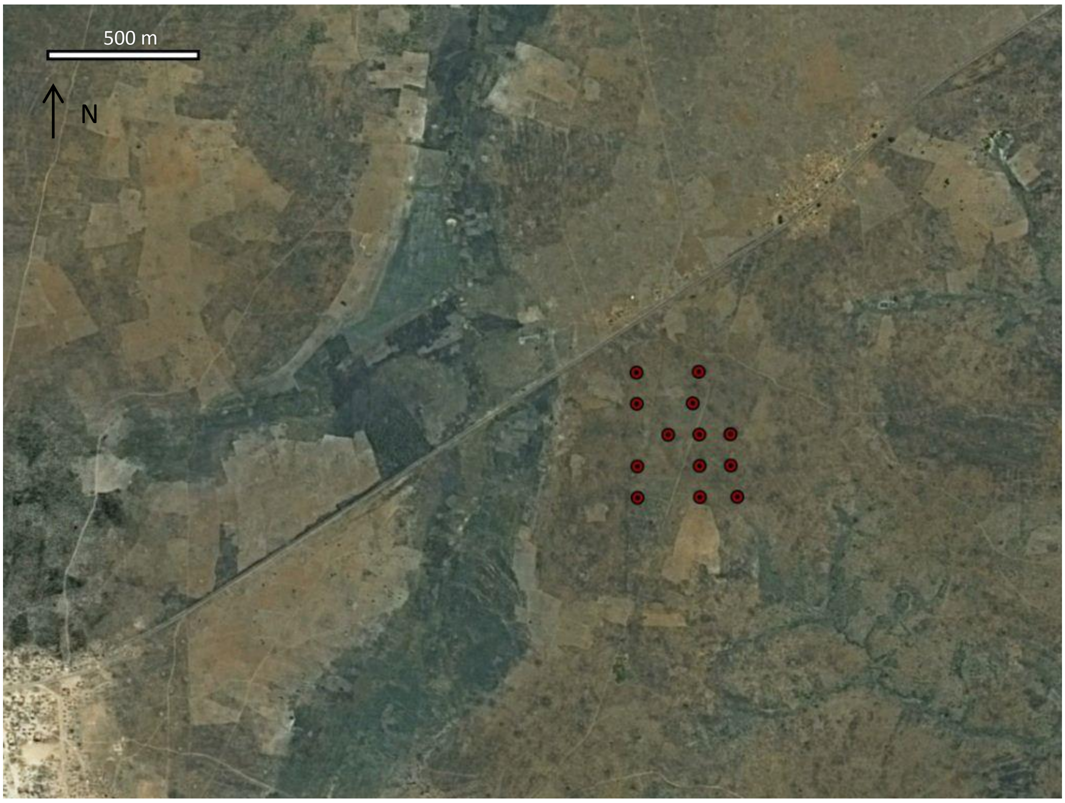

Figure 8. Surroundings and sample plot composition of measurement area A. Red markers point the sample plots included in the study (not in scale). Community of Chimbonila is visible in the southwest corner of the picture. Lichinga-Marrupa highway next to the measurement area is also visible. Notice the two shifted points and missing observations. The latter was due mosaics of active agriculture (not detectable in picture because of the fast land use dynamics of the area). Map compiled with Google Earth (aerial photos from 2013).

The relative proximity of the provincial capital Lichinga carried a notable effect on the whole landscape surrounding the field measurement area A. Trees were generally unable to grow mature at this distance from the city before being harvested and made into charcoal. This already generated an open type of landscape. The deforestation was ultimately caused by agricultural land use pressure from the community of Chimbonila, resulting in what appeared to be an intensively managed mosaic of active agriculture and fallow land widely around the community. Area A was a pure representative of the land use of this type (Figure 8), and hence selected as a field measurement area. There were also signs of recent fire present on part of the plots measured on the area, indicating occurrence of prescribed burning.

Area B

Area B was the primary area at which open miombo was measured in this study (Figure 9). The measurement site was located in the district of Sanga, about 5 km south from the community of Malulu housing a district administrative center. The straight distance to the city of Lichinga was about 40 km. The area was accessible by a small road and a number of paths.

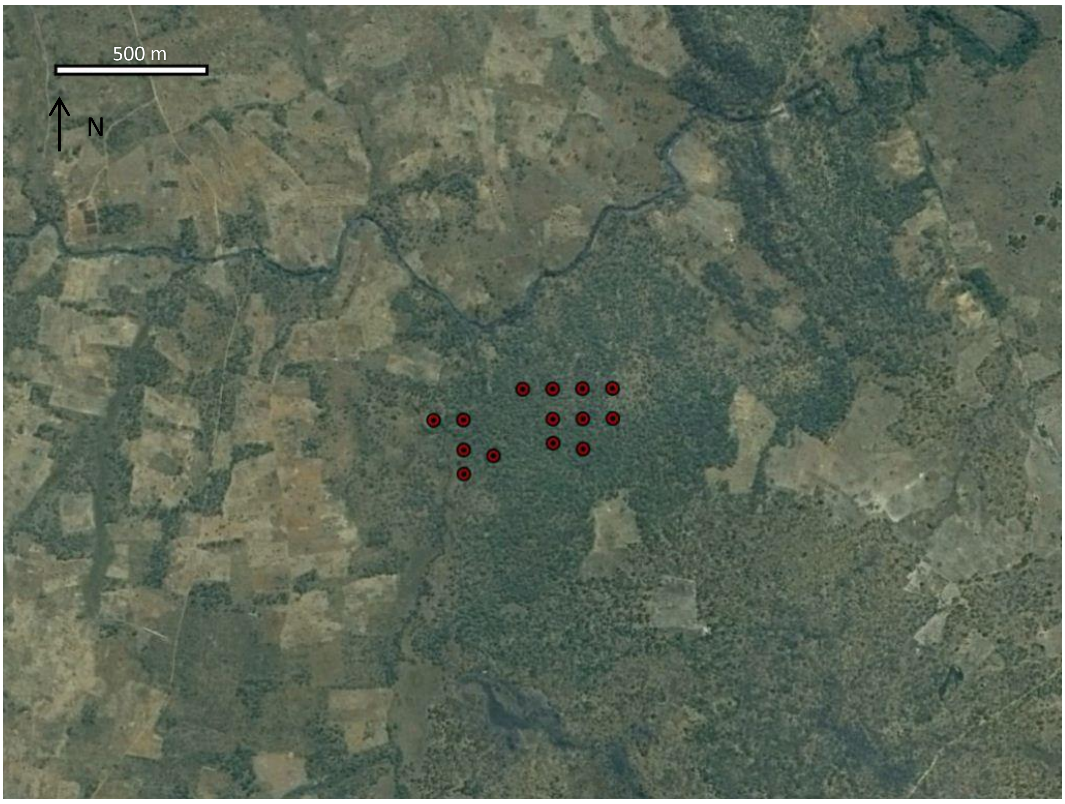

Figure 9. Surroundings and sample plot composition of area B. Red markers point the sample plots included in the study (not in scale). The grid was divided into two parts due exclusion of points representing wrong land cover. The forest clearance is too recent to be visible in the picture. Notice the two shifted points. Map compiled with Google Earth (aerial photos from 2013).

Area B was located right behind the fields of the community members, and processes of ongoing deforestation and forest degradation were observed in the woodlands. The latter appeared as fuelwood collection, whereas the former was due clearance of new agricultural land. A total of 23 plots were visited at the area, 14 of which were included in the study. The rest of the plots fell either under active agriculture, other woody vegetation or cleared road. It can be seen in Figure 9 how the grid was divided into two sections, because recently cleared new machambas fell in between. Even though some plots were discovered to have a naturally low tree cover, the primary reason for the less than 40 % tree cover in the area was identified being biomass removal by humans. Signs of cutting were common and piles of prepared fuelwood were waiting for transportation by forest paths. However, the level of degradation was still moderate and the site was easily identifiable as mature miombo woodland.

A soil different from the other measurement areas was observed at area B. The other measurement areas generally demonstrated red clay soil, but the soil at area B was completely grey of color. However, the soil characteristics were not evaluated according to any official criteria in the scope of this study.

Area C

Dense miombo plots were measured solely at area C. The area was a part of a large, relatively undisturbed patch of miombo extending to the both sides of the road connecting the communities of Muembe and Chiconono (Figures 7 and 10). The measurement area was located about 12 km northeast from Muembe. The straight distance to the city of Lichinga was about 60 km.

Area C represented closed, mature miombo with full tree cover present. No visible signs of cutting of trees or other degradation processes were observed in the area. The likely reason for the woodland to still remain undisturbed was that it stood far enough from major settlements, including the provincial capital with major charcoal markets. A total of 16 plots were visited at the area, 13 of which were measured in the study (Figure 10). Three plots were dropped out: one represented open miombo, one was located on a dry stream bed and one in proximity of the road had been recently cleared for machamba. The latter testified for deforestation making its way to the area, through access by the road.

Figure 10. Surroundings and sample plot composition of area C. Red markers point the sample plots included in the study (not in scale). Road from Muembe to Chiconono is visible next to the measurement area. Map compiled with Google Earth (aerial photos from 2013).

Terrain of area C had generally higher degrees of slope than the other measurement areas of the study. A slope greater than 10 % was recorded on seven plots. There was also evidence of past low-intensity fires on a few plots, though none of them had burned after the previous growing season.

Area D

Area D was the primary area for measurement of other woody vegetation in this study. The area was located in proximity of a relatively small roadside community by the road leading from Lichinga-Marrupa highway to Muembe (Figure 11). The nearest major settlement was the community of Mapaco about 4 km southwest from the area. The straight distance to the city of Lichinga was about 30 km.

Area D had been subjected to heavy cutting and woody biomass removal, and hence the level of forest degradation was high. A total of 25 plots were visited at the area, only 13 of which were included in the study (Figure 11). Active machambas only represented two of the excluded plots. Open miombo represented three, and seven of the excluded plots either represented pure fallow land (abandoned machambas) or totally deforested areas appearing as shrubby grasslands, equal to fallow land in vegetation characteristics. This demonstrates well the position of the other woody vegetation as a heterogeneous transitional class occurring between miombo woodlands and fallow lands. The plots measured in the study generally had notable stem counts of small diameter trees below and over DBH of 5.0 cm, while trees with a DBH exceeding 20 cm occurred sparsely. Wildfires had been common in the area, and part of the measured plots had lost the most of their herbaceous vegetation cover in fire.

Figure 11. Surroundings and sample plot composition of area D. Red markers point the sample plots included in the study (not in scale). The area was bordered by fallow land and active agriculture in the east and west, and mosaics of open miombo and fallow land in the south. Two fallow land plots were excluded in the middle of the grid. The road leading from Lichinga-Marrupa highway to Muembe is also visible. Map compiled with Google Earth (aerial photos from 2013).

Area F

The only area containing plots included from two different LUCs was area F, measured as an additional site. The area was located by the route from Chimbonila to Muembe like area D, but 10 km further to the distance of Muembe. The straight distance to the city of Lichinga was about 40 km. The area had a number of small roadside communities nearby, but no major settlements.

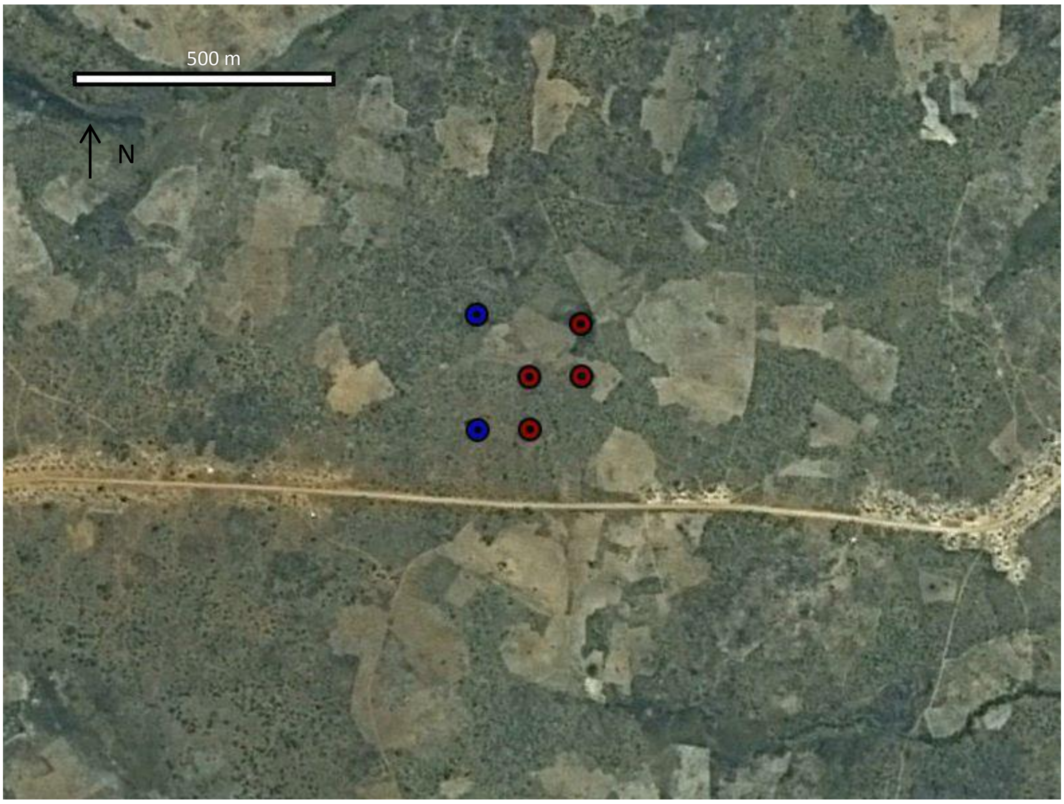

Figure 12. Surroundings and sample plot composition of area F. Blue markers point the open miombo sample plots and red markers point the other woody vegetation sample plots included in the study (not in scale). A single plot has been shifted towards north due land use border. The road leading from Lichinga-Marrupa highway to Muembe is visible south from the area. Map compiled with Google Earth (aerial photos from 2013).

Area F represented a mosaic (and also a transitional zone) between open miombo and other woody vegetation. Two plots of open miombo and four plots of other woody vegetation were measured at the area (Figure 12). Other of the open miombo plots represented secondary miombo, re-growing after disturbance. Otherwise the stand characteristics were generally similar with the ones described with areas B and D.

Two more plots were visited at area F in addition to the six measured, but one was excluded as fallow land and the other due wildfire present at the site by the time of the measurements.

Forest plantation stands

Forest plantations were measured at 11 different stands of mostly different ages, with the distribution presented in Table 5 below. The forest plantation measurement sites were significantly more scattered than those of the native vegetation (Figure 13), though stretching over a geographically smaller area (Figure 7). Distance to the city of Lichinga varied approximately between 5 and 15 km. Since the stands were chosen based on the provided stand information, their location did not carry importance in the process.

Table 5. Number of sampled forest plantation stands by age group. The first two age groups of eucalypt include two stands each, planted on slightly different time but addressed as single groups herein. The age is given in base ten system.

Species group	Age	n (stands)	n (plots)
Eucalypt	0.6/0.7	2	5
	1.6/1.7	2	5
	8.6	1	5
Pine	1.7	1	3
	4.7	1	4
	5.6	2	5
	7.6	1	3
	8.6	1	4

The included stands were relatively homogenous in terms of stem count within the species groups. Altogether, plantations represented a rather homogenous landscape across the study site, only varying in the size of the trees between the sites.

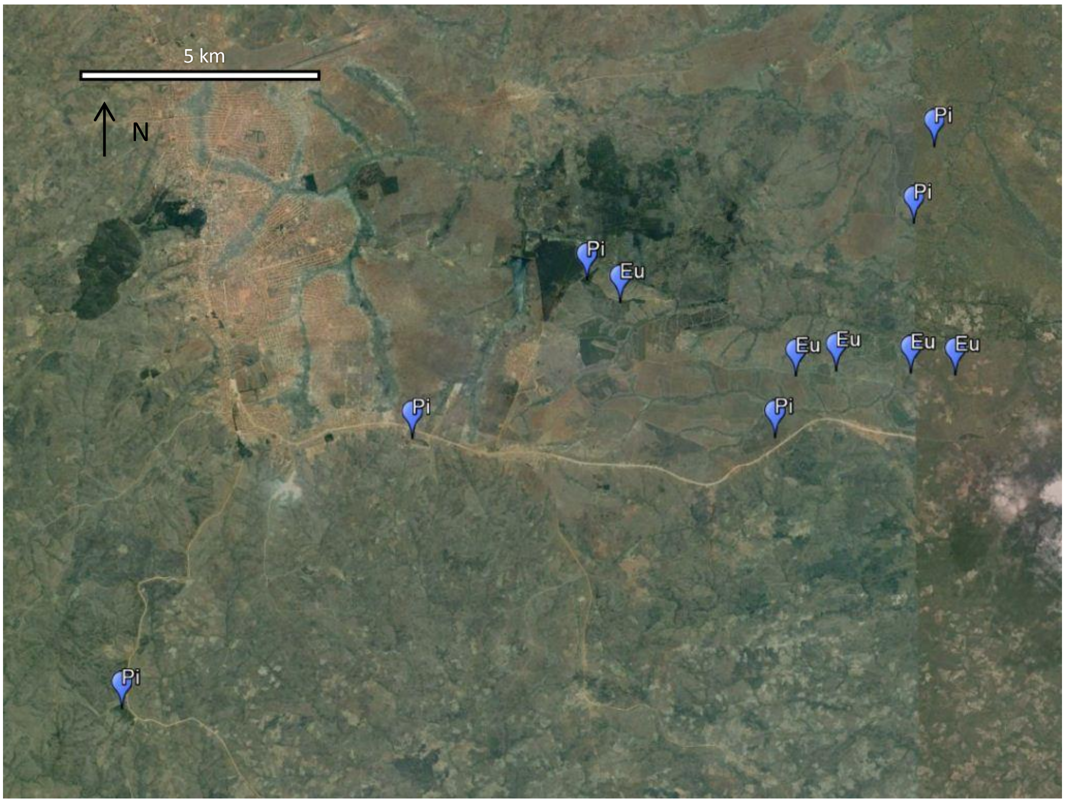

Figure 13. Locations of the plantation stands sampled in this study. The urban settlements of Lichinga city are a dominant element on the northwest side of the map. Eu = Eucalypt stand, Pi = Pine stand. Map compiled with Google Earth (aerial photos from 2013).

2.5 Field measurements

2.5.1 Sample plot structure

The plots recorded in this study were intended to be temporary. Circular plot type was chosen to be used in measurements of tree aboveground biomass due to its efficiency as temporary plot. Furthermore, a nested plot structure was adopted to make tree measurements increasingly efficient on the native vegetation LUCs, which included a wide DBH variation. Both above-mentioned measures are recommended by carbon survey guidelines presented by Walker et al. (2012).

Walker et al. (2012) also suggest general recommendations for circular plot radiuses concerning certain DBH classes. They point out however, that local modifications are necessary on savanna-type woodlands that may include high variation both in DBH and stand density. Test measurements were performed in this study prior to the actual field survey to adjust the nested plot structure for optimal sample size. This was done both on native vegetation and forest plantations land use classes. Based on results, the plot structure illustrated in Figure 14 was adopted with the following DBH classes and circle plot radiuses (Table 6).

Table 6. Circular plot design for recording trees in this study. Two nested circles were used on the native vegetation land use classes. A single circle was sufficient in recording the relatively homogenous stands of forest plantations.

Native vegetation		**Forest plantations**	
DBH (cm)	Plot radius (m)	DBH (cm)	Plot radius (m)
5.0–19.9	7.98	0.0–	7.98
20.0–	20.00		

A minimum DBH of 5.0 cm was applied for trees of the native vegetation LUCs. Trees below this limit were considered as saplings and assessed in destructive sampling with shrubs.

There were fixed subplots included in the plot structure for destructive sampling of non-tree aboveground vegetation (Figure 15). A circular plot, placed in the center of the plot design with a radius of 2.0 meters, was used to sample shrubs and saplings. A square shaped clip plot of 1.0 m^2 was used to sample herbaceous vegetation. Both subplots followed design recommendation by Walker et al. (2012). The plot structure also carried four fixed positions for taking disturbed soil samples. Additionally, a soil bulk density sample was taken from a fixed position on part of the plots. The soil sampling design is further described and illustrated in 2.5.5.

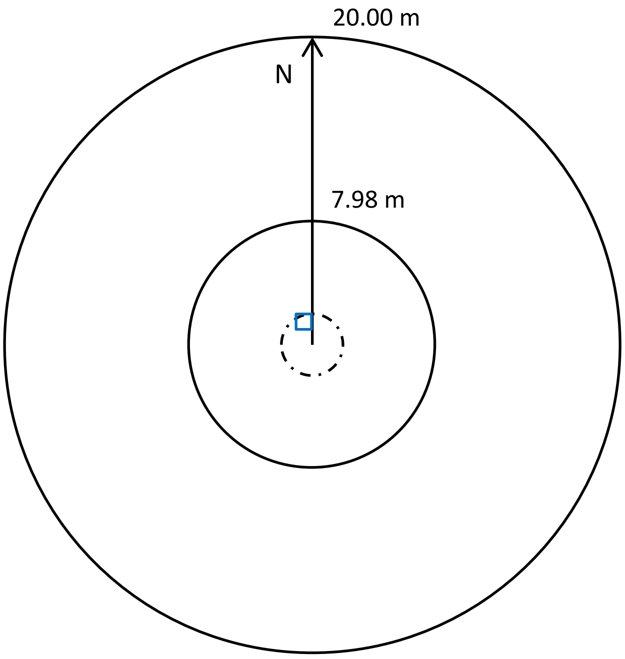

Figure 14. Sample plot illustration. For recording trees on forest plantations, only the smaller circle (r = 7.98 m) was applied. The dashed circle represents the subplot on which shrubs and saplings were sampled (r = 2.0 m). The clip plot (1.0 m^2) for sampling herbaceous vegetation is also presented. N marks direction to north.

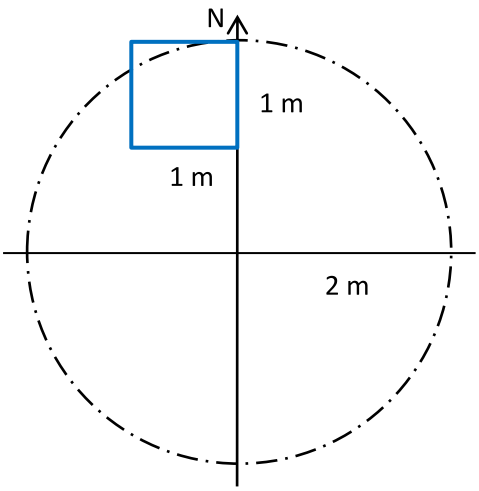

Figure 15. Subplots applied in destructive sampling. A magnification from Figure 14. To avoid trampling of the herbaceous vegetation, the 1.0 m^2 clip plot was not placed in the center of the design.

2.5.2 Mapping the plots

Determining location of the sample plots in the field was basically a similar process in both of the land use class groups, the only difference occurring in the principle of determining the center of the first plot. On native vegetation, the starting point was predetermined by obtaining coordinates randomly from aerial photos of the sampling area in Google Earth. On forest plantations, the stand subject to sampling was entered and the starting point was chosen in the field by throwing a suitable object, typically a stick, randomly in the air and determining coordinates of the landing point with a GPS device. In both cases, the coordinates for the following points in the grid were then calculable.

The coordinates of the following plots were not pre-determined, only the directions in which the grid was intended to be extended. The sample plots were labeled and numbered in the order they were reached, mapped and included in the study on field. Coordinate determination was done using a GPS device (Garmin GPSMAP 64s). Excluding the plantation first plot case described above, a new plot was found using GPS orientation to reach the approximate plot center. A random spot was then picked for the exact plot center location inside the precision provided by the GPS device, which was typically ± 3–4 meters.

Plots that were found in field to represent a land use class other than the grid was intended to survey, or another land use falling completely outside the scope of this study, were excluded from the survey. This caused missing observations in regular survey grids, since the phenomenon was not uncommon due the fast dynamics of the landscape on the study site. The only exception to this principle was additional survey area F, where both open miombo and other woody vegetation plots were included. On plantation grids, every plot was required to fall under the same stand.

If a plot was found to fall partially on a border of the surveyed land use class on native vegetation, the plot location was shifted 20 meters instead of excluding the plot. The shifting was applied in a principal compass point directing away from the border and towards the surveyed land use class. On plantations, the length of the shifting was 10 meters, which was however only applied on one plot.

Upon determining the plot center, slope on the plot was measured using the ascent (%) scale of the hypsometer and recorded if it was 10 % or above.

2.5.3 Measurement of trees

Trees were defined as woody plants with a minimum height of 1.3 meters and a minimum DBH of 5.0 cm in this study. The latter criterion was only applied on native vegetation LUCs, since juvenile plantation stands generally consisted of trees with a smaller DBH.

The sample plot boundaries for recording trees were determined using a nylon rope. A rope with a total length of 20.00 meters and a mark at the length of 7.98 meters was used on native vegetation. On plantations, a rope with a total length of 7.98 meters was used. Both of these ropes also had a mark at the length of 2.00 meters for the shrub & sapling subplot. Either of the two major soil sampling tools (Figure 18) was generally used as a plot center pole at this stage of the measurements.

All living trees inside a plot were recorded. Trees were considered living if they included green leaves or if fresh phloem was found under the bark. The second criterion was included since some miombo trees were having their leaves dropped for dry season while this study was conducted. The recording of trees started from a non-fixed direction, proceeding clockwise until the first measured tree was reencountered. The first measured tree was always flagged to ensure later recognition. Trees along the plot boundaries were considered to be inside the plot if their assumed point of germination was.

DBH and species were recorded from every tree. DBH was measured using a diameter tape (Hultafors, 3 m). A local guide identified species with local name in the language of Chiyao. Tree height was recorded from every fourth tree representing the same species, counted in the order they were encountered on plot. Counting was done over the plots on a same measurement area, but for each measurement area separately. This was the principle applied on plantation stands as well. Additionally, height was recorded from every tree with a DBH of 40.0 cm or above. As a general principle, height of tall trees was measured using hypsometer and height of low trees was measured using either a 4 meter or a 5 meter pole with scale. The threshold height separating the two methods was about 6 meters.

Practically, hypsometer was applied on dense miombo, open miombo, plantation stands of 5 and 8 years of age and tall trees on other woody vegetation. A pole was applied on the rest. Pole being absent on height measurements on the miombo land use classes, hypsometer was used down to about 4 meters and height of the lowest trees was estimated visually in relation to breast height.

Branching was common on tree species of the native vegetation, often occurring already below the breast height. Guidelines presented by Walker et al. (2012) were applied with the DBH measurements. A stem branched below breast height was recorded with the branches as separate individuals with their own respective DBHs. If branching occurred between 1.0–1.3 meters, the DBHs for the branches were measured another 30 cm above the branching point to avoid recording anomalies in stem form. Similar principal was applied with stem buttresses.

An exception was made on forest plantation LUCs, in the rare case of plantation tree species individuals branching into two stems below breast height. To avoid recording false number of stems on stand, only the major branch was measured as a stem and the minor branch or branches became excluded from the survey.

2.5.4 Measurement of shrubs and herbaceous vegetation

In this study, shrubs were defined as woody plants that did not reach the definition of tree in their mature state. Juvenile trees that had not reached the definition of tree due their limited age were defined as saplings. Both shrubs and saplings were measured in the same merged group, addressed with destructive sampling.

The boundaries of the circular plot for shrub destructive sampling were determined using ropes with a mark at 2.00 meters. All woody vegetation that did not reach the definition of tree was cut down using a machete from the plot area. Cutting was done as close to the surface of the ground as possible. The material was then weighed fresh on a bag with a hanging scale (Berkley 50 lb digital scale). Each weighing was repeated four times to reduce error caused by scale inaccuracy.

Destructive sampling was also applied on herbaceous vegetation. The boundaries of the 1.0 m^2 clip plot were shaped from 1.00 meter PVC pipes constructed around the vegetation. Direction to north, determined with a compass, was needed at this stage to enable the correct plot orientation. The 90 degrees in plot corners were determined visually. Figure 16 shows two examples of the clip plot after the sampling has taken place.

Herbs were cut from the clip plot area using knife and machete, and then packed and sealed into labeled paper bags. All vegetation aboveground parts were intended to be collected while excluding the litter. The paper bags were then transported back from the field for weighing. The vast majority of the plant material collected was dead and dry because the field work took place on dry season. Prior to weighing, the bags were nevertheless dried for several days under the sun in daytime to ensure that remaining moisture was removed to the extent possible without an access to oven. The digital scale used in the weighing carried a precision of ± 5 g.

Figure 16. Herbaceous vegetation clip plot after destructive sampling on two very different sites. The left picture is from a pine stand 7.6 years of age and low tree cover, and the right picture is from a closed eucalypt stand 8.6 years of age. The site in the left picture has a dense layer of herbaceous vegetation. The site in the right picture shows exceptionally high amount of litter, left outside of the sampling protocol, but barely any herbaceous vegetation.

2.5.5 Soil sampling

The soil organic carbon (SOC) survey in this study was limited to consider the topsoil (30 cm) only. Two types of soil samples were collected: disturbed and volumetric. The former were used to determine soil C content and the latter to determine soil bulk density (BD).

Disturbed samples were collected from every plot at four positions fixed into the plot structure, one in every principal compass point. The obtained soil material was combined in pairs into two composite samples per plot. Volumetric samples, referred as BD samples herein, were collected from every second plot on native vegetation LUCs. The collection was done in the order the plots were mapped on each primary area, starting from the first plot the area. On forest plantation LUCs, a BD sample was collected from the first plot of each new measurement area (stand) in the order the areas were measured. BD samples were collected until a total number of five samples per each LUC of the study had been obtained. No volumetric sampling took place after this point.

As shown in Figure 17, the positions from which disturbed samples were collected differentiated between native vegetation and forest plantations. The principle was to take soil samples inside the same plot on which trees were measured (Walker et al. 2012). On native vegetation, the samples were collected along the sphere of the circular plot with 7.98 meters radius, since this placed inside the nested structure. However, on forest plantations, the same circle represented the boundary of the plot, rather than being inside of it. To conduct the soil sampling inside the plot also at forest plantations, the procedure was shifted inwards along an imaginary sphere of a circle with a 5.00 meters radius.

Disturbed samples were collected using a soil drill (Figure 18a). The soil was drilled down to 30 cm and the soil material obtained was collected into a bag. The principle was to get the same relative amount of soil from each depth between 0–30 cm. On hardest of the soils, the soil hammer (Figure 18b) was used as an aid to help penetrate the soil. Disturbed samples were then combined into two composite samples by merging the material as north-east and south-west pairs (Figure 17). The soil material was homogenized on location by mixing it thoroughly, and about 300 g was packed and labeled while the rest was discarded.

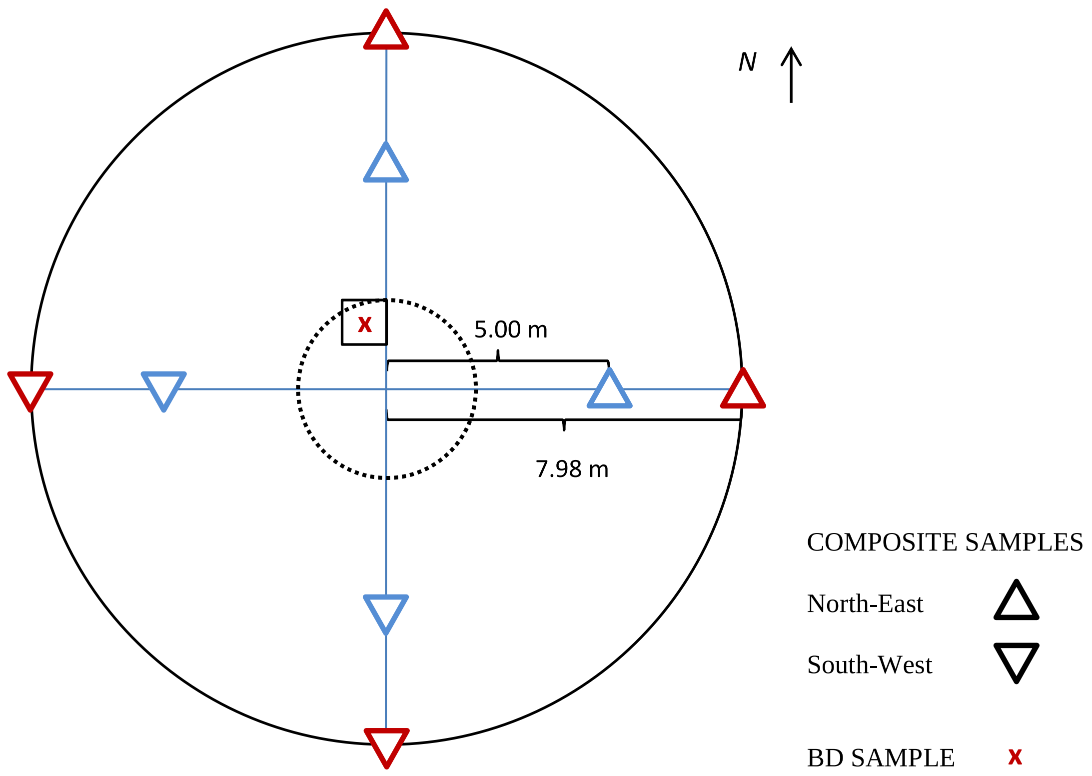

Figure 17. Soil sampling design. Red triangles represent the soil sampling pattern on native vegetation LUCs and blue triangles represent the soil sampling pattern on forest plantation. BD sample was always collected from the same position in the middle of the herbaceous vegetation clip plot.

The final soil samples that were used in the analysis were acquired by collecting subsamples of 10–15 grams from each collected composite sample. Out of the theoretical maximum of 186 composite samples, a total of 180 samples were eventually delivered to analysis. Three samples failed to be collected due high stone content in soil and three samples were lost in transportation.

BD samples were collected using a soil hammer (Figure 18b). The hammer was loaded with three volumetric soil cylinders, two of which were basically unnecessary from the study point of view, and the soil was penetrated by striking repeatedly down to the point where the end of the cylinder head was in line with soil surface. It was assumed that the contents of the middle cylinder would remain most undisturbed (compression versus material loss) in the process, hence that one was chosen to be collected as the sample. The middle cylinder was separated from the other two using spatula and knife, then sealed and labeled for analysis. The contents of the other two were discarded.

The total amount of BD samples collected in this study was limited by the number of soil cylinders required for sampling. There were 30 of them. The height of the cylinders was 5.0 cm, and since the middle cylinder was the one collected, the resulting BD samples covered soil between depths of 5.0–10.0 cm.

Fig. 18a

Fig. 18b

Figure 18. Soil drill (Fig. 18a) used to obtain the disturbed soil samples and soil hammer (Fig. 18b) used to obtain the volumetric soil samples of this study. Depth of 30 cm is marked with blue stripe in the shaft of the drill. The soil hammer is shown opened, with one of the three cylinders included in the cylinder head visible.

2.6 Soil sample analysis

The soil composite samples were dried in paper bags in a laboratory oven for four days in temperature of 50°C in order to remove possible moisture. The carbon content of the samples was analyzed with varioMAX C/N-analyzer. 700–900 mg of soil material from each sample was required in the analysis. The analysis was conducted twice for 12 randomly picked samples in order to test the precision of the analysis. The volumetric soil samples were dried and weighed for determination of BD (dry volumetric mass of the soil).

2.7 Calculations and data processing

2.7.1 Allometric equation for native vegetation

The final biomass result for individual trees of the native vegetation LUCs was calculated using an allometric equation. The equation (1) applied was a site-specific collective allometric equation for native miombo species, developed in the PAIMO project framework (Macia, unpublished):

$$BM = 0.171 * DBH ^\wedge 2.347 \tag{1}$$

where BM is dry biomass. As can be seen in the equation (1), DBH was applied as the sole explanatory variable for BM. The same equation was used with every tree measured. Each individual tree biomass was then converted into a figure per hectare (Mg ha^{-1}) based on their respective circular plot area. Total tree aboveground biomass (Mg ha^{-1}) per sample plot was calculated as a sum of these figures. Tree aboveground biomass per each LUC was calculated as the arithmetic mean of the sample plot results from the LUC. Additionally, standard deviation (S.D.) was calculated to describe the distribution of the results.

2.7.2 Forest plantation growth estimation

The growth for forest plantations measured in this study was estimated based on site quality indices (SI) they demonstrated in their height development, and growth models representing the respective SIs.

The age and height data recorded from forest plantation LUCs was plotted against graphs drawn from existing growth and yield tables (Figure 19). The growth and yield tables of *Eucalyptus grandis* and *Pinus patula* from the South African forestry handbook (Kassier & Kotze 2000) were used herein due their geographical relevance. The height growth on the measured plantations was compared to existing figures (Kassier & Kotze 2000), making it possible to estimate the average site quality index (SI) of the measured sites for both eucalypt and pine stands (Figure 19). A collective SI was determined for both species groups, with eucalypts representing the lowest of the three indices and pines the medium index. Two age groups of pine were excluded from the SI determination, since the correspondent stands were found to demonstrate significantly reduced growth compared to the others (Figure 19b).

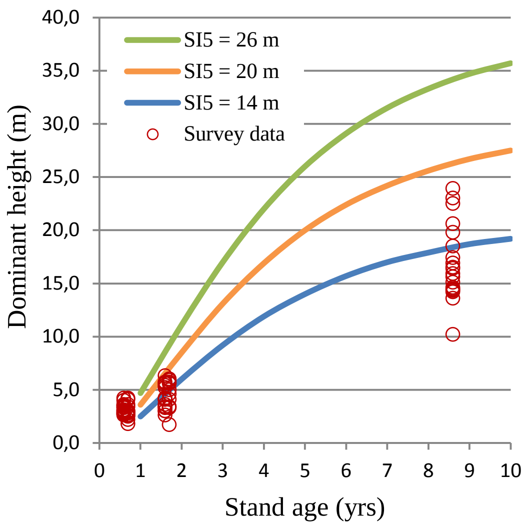

Fig. 19a

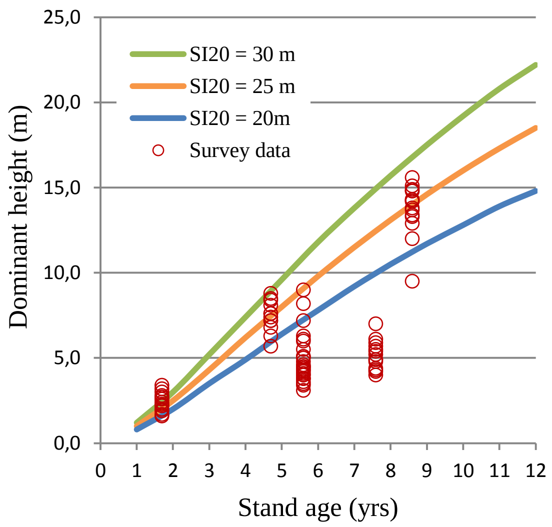

Fig. 19b

Figure 19. Site quality index curves and heights measured in this study for eucalypt (Fig. 19a) and pine (Fig. 19b). The SI is determined by dominant height of the stand on a certain age. Eucalypt stands were found to represent the lowest site index (SI_5 = 14 m) and pine stands the medium site index (SI_{20} = 25 m). Stands from two age groups of pine (5.6 and 7.6 years) demonstrated poor height growth and were excluded from the index determination. Site quality index curves drawn after Kassier & Kotze (2000).

The growing schemes of the plantations were provided by the owner company, enabling their comparison with the existing growth tables (Kassier & Kotze 2000). Since initial stem densities, harvest timings and harvest intensities were relatively similar between the intended growing schemes and the growth tables, it was possible to apply the growth tables in the plantation growth estimation as they were. Eucalypts growth was estimated over a rotation period of 8 years and pine growth was estimated over a rotation period of 23 years.

The average (m^3 ha^{-1}) volume stock for the reported rotation period was calculated as an arithmetic mean of the yearly volume stocks during the rotation period, given at the growth table of the correspondent site quality index. Considering the years in which thinnings of the pine stands took place, growth tables reported two stock volumes (before and after thinning). An arithmetic mean of these two was used in the average stock calculation.

Relevant biomass conversion and expansion factor (BCEF) suggested by IPCC (2006) was used to convert the calculated average volume stock into stock of biomass (Mg ha^{-1}) respectively for eucalypt and pine plantations. Finally, the figures were converted into terms of carbon with a biomass C content factor also presented by IPCC (2006). The resulting values represented the average carbon sub-stocks of trees for the forest plantation LUCs.

Because of the different methodology, it was not possible to calculate S.D. for the estimated C stocks of trees on plantation LUCs. To address this shortcoming, S.D. of the recorded tree heights was applied. Relative S.D. (as percentage of average height) was calculated separately for each age class, and then the arithmetic mean of these figures was calculated for both LUCs. The resulting coefficients were applied on the estimated average plantation tree C stocks, which provided a rough estimate for the C stock distribution. The same coefficients were also applied when distributions of the plantation aboveground total C stocks and the belowground C stocks were estimated. Height distribution was chosen to be utilized in the S.D. estimation because it behaves relatively independent of site density and forest management, which might vary between the measured stands.

2.7.3 General calculations

Belowground carbon

Vegetation belowground biomass was estimated based on a meta-analysis of R:S ratio studies by Mokany et al. (2006), and their biome-specific suggestions. The R:S ratio applied for native vegetation LUCs was categorized as "Tropical/subtropical/temperate woodland" and valued 0.322 with a reported standard error of 0.085. The ratio applied for forest plantation LUCs was categorized as "Tropical/subtropical dry forest/plantation", and it valued 0.275 with a reported standard error of 0.003. The ratio was reported applicable for stands with shoot biomass exceeding 20 Mg ha^{-1}, and the plantation growth estimation process showed that this requirement was fulfilled forest plantation stands on average.

The ratios were used to calculate an estimate for the belowground C stock from the total aboveground C stock independently for each plot. Due to lack of reliable estimates for shrub and herbaceous vegetation root allometrics in the ecosystems covered in this study, the belowground C stocks for trees, shrubs and herbaceous vegetation were not estimated separately. Instead, a single figure for total belowground C, based on total aboveground C, was calculated.

An exception was formed by the fallow land LUC, which was the only land use class with herbaceous vegetation forming a major part of the total aboveground C stock (30 %). Grasslands generally carry significantly higher R:S ratios than woodlands (Mokany et al. 2006), so the contribution of herbaceous vegetation roots to fallow land belowground C stock was calculated separately from trees and shrubs. A higher ratio valued 1.887 (standard error 0.304) and categorized as "Tropical/subtropical grassland" by Mokany et al. (2006) was applied.

Soil organic carbon

The analysis by varioMAX provided the carbon content as percentage of the mass of the soil. The result was converted into a C stock per hectare with the following equation (2) by Pearson et al. (2005):

$$C_{stock} = BD * d * C_{\%} * 100 \quad (2)$$

where BD is the bulk density as g cm^{-3}, d is the soil sampling depth as cm, $C_{\%}$ is the soil carbon content as decimal fraction and C_{stock} is the resulting soil carbon stock as Mg ha^{-1}. The sampling depth of 30 cm used throughout the study was applied. The applied BD values were calculated separately for each LUC as the arithmetic mean of the samples from the LUC in question.

Applied conversion factors

The calculated tree biomass results on native vegetation LUCs were converted into terms of carbon using a conversion factor 0.47 (IPCC 2006). On forest plantation

LUCs, modelled stand volume aboveground was first converted into biomass with BCEFs: the factors applied were 0.8 for eucalypt and 0.55 for pine (IPCC 2006), determined by the type of trees (hardwoods and coniferous) and their estimated average stock volume. The subsequent conversion into terms of carbon was calculated again with the conversion factor 0.47 (IPCC 2006).

Weighed fresh biomass of shrubs and saplings was converted straight into terms of carbon by multiplying it with a conversion factor 0.25. The mass of the weighing bag was first subtracted from the fresh biomass result. The conversion factor 0.25 was a result of assuming 50 % carbon content of the dry mass and 50 % average moisture content of the shrub and sapling fresh biomass. The latter assumption was supported by Mate et al. (2014), who measured mean moisture contents very close to 50 % for stems, branches and leaves of three major Mozambican tropical tree species.

Herbaceous vegetation was weighed dry, and the resulting dry biomass was converted into terms of carbon by assuming carbon content of 50 %. The weight of the paper bag containing the weighed material was first subtracted from the result. The carbon result was further converted into a figure per hectare (Mg ha^{-1}) based on the clip plot area.

Slope correction

If a slope of 10 % or above was recorded from a plot, a slope correction was applied on the area of circular plots for trees, as well as the circular plot for shrubs and saplings, prior to converting the plot biomass result into a figure per hectare. The recorded slope was converted into degrees and the correction was calculated with equation 3 (Walker et al. 2012):

$$r_{corrected} = r_{measured} * \cos(\alpha) \quad (3)$$

where r stands for plot radius and α stands for angle in degrees. The slope corrections were only applied in calculations concerning biomass on native vegetation LUCs. On forest plantations there was no need for action since no slope of 10 % or greater was measured on any of the plots.

2.7.4 Statistical analysis

It was tested whether the differences between the carbon sub-stocks and total carbon stocks of different LUCs were statistically significant. The testing was conducted as ANOVA with Tukey's honest significant difference test as the method. Tukey's honest significant difference was chosen to be applied instead of the standard t-test to reduce the risk of type I error resulting from conducting multiple comparisons simultaneously. Equal variances between the groups were assumed. Testing was conducted with confidence interval of 95 %.

The analysis could not be conducted on the carbon sub-stock of trees on the plantation LUCs, since the data from growth estimation was incompatible with other sub-stocks and LUCs. Same applied for any carbon stocks including a plantation tree stock as a component. The comparisons had to be made based on the averages only. It was also possible to make some conclusions from the height data -based estimates of S.D.

The reliability of soil sample analysis was also addressed statistically by testing how well the data from the duplicate samples matched each other. The test was conducted as simple linear regression between the two sample sets.

All statistical testing was conducted using SPSS software (IBM SPSS Statistics for Windows, Version 21.0).

3. RESULTS

3.1 Vegetation aboveground carbon stocks

3.1.1 Native vegetation

Dense miombo was found to represent the highest total aboveground carbon stocks on the native vegetation LUCs, with an average of 37.65 Mg ha^{-1}. Fallow land represented the lowest C stocks with an average of 2.04 Mg ha^{-1}. The maximum and minimum recorded in the study also placed on dense miombo and fallow land, with respective values of 0.46 and 51.30 Mg ha^{-1}. Open miombo and other woody vegetation placed in between the two classes with average C stocks of 27.47 and 11.41 Mg ha^{-1}, respectively. All paired comparisons between the classes were statistically significant. The mean BA values recorded from dense miombo and open miombo were 12.2 m^2 and 8.8 m^2 respectively.

The results show that the total aboveground C stock was determined primarily by the size of the C stock of trees that also demonstrated statistically significant difference between all of the native vegetation LUCs (Figure 20).

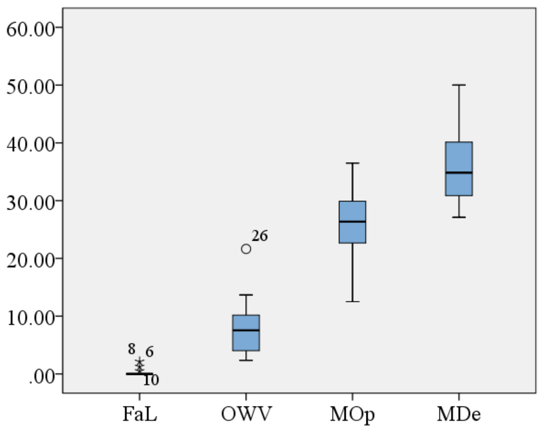

Fig. 20a. Trees

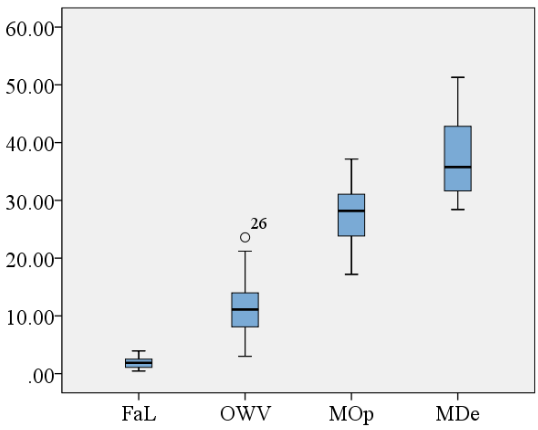

Fig. 20b. Aboveground total

Figure 20. Box-and-whisker plots for carbon stock of trees (Fig. 20a) and aboveground total (Fig. 20b) of native vegetation LUCs. The figures are shown as Mg ha^{-1} (y-axes). The boxes represent observations between 25^{th} and 75^{th} percentile. The whiskers represent minimum and maximum values up to a limit of 1.5 times the height of the box. Observations beyond this point are considered outliers and marked as circles. Asterisks mark outliers further than three times the height of the box. Dark thick line represents the median value. Land use classes: FaL = Fallow land, OWV = Other woody vegetation, MOp = Open miombo, MDe = Dense miombo. Figures drawn with SPSS.

The C stock of trees was found to be the largest of the three aboveground sub-stocks by far on both miombo classes and other woody vegetation, but only accounted for 15 % of the total on fallow land. Only three sample plots out of 13 contained any trees on fallow land, while the rest of the C stocks were constituted by shrubs & saplings and herbaceous vegetation. Other woody vegetation also included a notable C stock share of 24 % by shrubs & saplings, whereas both miombo classes were totally dominated by C stock of trees (> 90 %).

The distributions of shrub & sapling C stocks and herbaceous vegetation C stocks of the native vegetation LUCs are presented in Figure 22 of section 3.1.3 together with the correspondent results from the forest plantation LUCs. Section 3.1.3 also includes the results of their statistical analysis.

3.1.2 Forest plantations

The model-based plantation growth estimation resulted in average carbon stock of 20.24 Mg ha^{-1} for trees on eucalypt plantations and 33.00 Mg ha^{-1} for trees on pine plantations. The total aboveground C results for forest plantation LUCs are shown in Table 7, with the measurement-based figures for shrub & sapling and herbaceous vegetation C stocks included.

Table 7. Mean aboveground carbon stocks for forest plantations. The results are given as Mg ha^{-1} with S.D. included. † The figure is a model-based estimate, or has a model-based estimate as a component. ¶ The figure has been estimated based on tree height distribution data. Land use classes: EuP = Eucalypt plantation, PiP = Pine plantation.

LUC	Trees	Shrubs & saplings	Herbaceous	Aboveground total
EuP	20.24† ± 4.71¶	0.27 ± 0.36	0.54 ± 0.52	21.04† ± 4.90¶
PiP	33.00† ± 5. 92¶	0.48 ± 0.54	1.11 ± 1.32	34.59† ± 6.21¶

3.1.3 Combined aboveground

The total aboveground C stocks for all six LUCs are presented in Figure 21. C stock distributions for shrubs & saplings and herbaceous vegetation are presented in Figure 22.

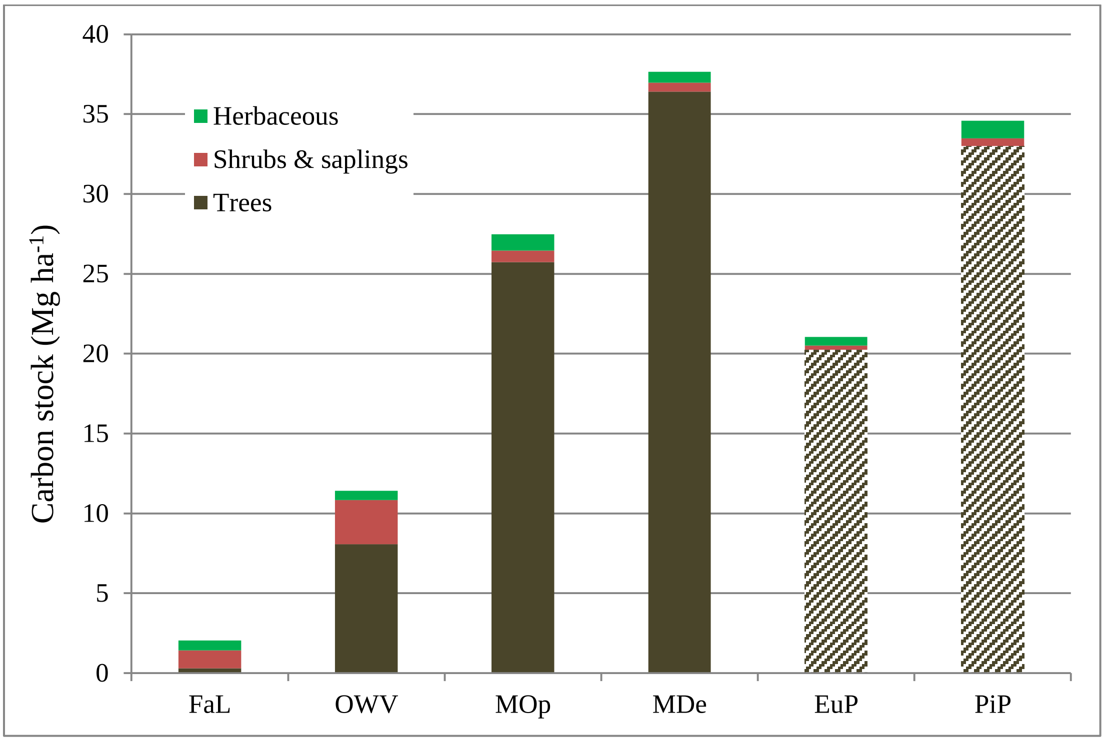

Figure 21. Mean total aboveground carbon stocks for all six land use classes of the study. Striped bars of EuP and PiP tree C stocks mark model-based estimates. Other figures are based on calculated arithmetic means of the measured data. Land use classes: FaL = Fallow land, OWV = Other woody vegetation, MOp = Open miombo, MDe = Dense miombo, EuP = Eucalypt plantation, PiP = Pine plantation.

The combined aboveground C stocks demonstrated a relatively steady ascent between the native vegetation LUCs in the order they are presented in Figure 21. The C stocks of eucalypt plantations and pine plantations were found to be of the same order of magnitude with the two miombo LUCs. However, C stocks of the both plantation LUCs remained below their closest miombo counterparts. Dense miombo demonstrated the highest aboveground C stock of all the LUCs but not with a superior difference, whereas fallow land had the smallest aboveground C figure by far.

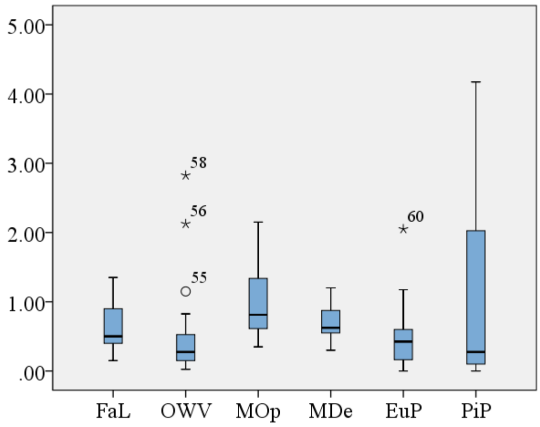

Fig. 22a. Herbaceous vegetation

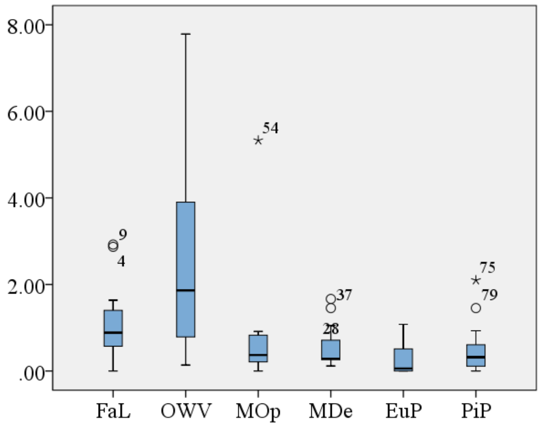

Fig. 22b. Shrubs & saplings

Figure 22. Box-and-whisker plots for carbon stocks of shrubs & saplings (Fig. 22a) and herbaceous vegetation (Fig. 22b) of all six LUCs of the study. The values are given as Mg ha^{-1} (y-axes). The boxes represent observations between 25th and 75th percentile. The whiskers represent minimum and maximum values up to a limit of 1.5 times the height of the box. Observations beyond this point are considered outliers and marked as circles. Asterisks mark outliers further than three times the height of the box. Dark thick line represents the median value. Land use classes: FaL = Fallow land, OWV = Other woody vegetation, MOp = Open miombo, MDe = Dense miombo, EuP = Eucalypt plantation, PiP = Pine plantation. Figures drawn with SPSS.

The only LUC with a shrub & sapling C stock that demonstrated any statistically significant difference in comparison with the others was other woody vegetation. The divergent distribution is clearly visible in Figure 22b. The difference occurred statistically significant when tested against any of the other LUCs. C stocks of herbaceous vegetation (Figure 22a) did not demonstrate any statistically significant differences between the LUCs. It can be seen in the Figure 22a that the shape of the C stock distribution observed on pine plantations differentiates from the others by being wider. However, it is centered around low values and the difference to other LUCs does not come close to exceeding the 95 % confidence interval.

3.2 Vegetation belowground carbon stocks

Since vegetation belowground C stocks were calculated as ratio-based figures of vegetation aboveground C, the belowground results (Table 8) generally reflect the aboveground results. The relative differences occur in fallow land LUC and forest plantation LUCs, where different calculation technique and different R:S ratio were used, respectively.

Table 8. Mean vegetation belowground carbon stocks. All results are shown as Mg ha^{-1} with S.D. included. † The figure is calculated from a model-based estimate. ¶ The figure has been estimated based on tree height distribution data. Land use classes: FaL = Fallow land, OWV = Other woody vegetation, MOp = Open miombo, MDe = Dense miombo, EuP = Eucalypt plantation, PiP = Pine plantation.

LUC	Vegetation belowground C
FaL	1.63 ± 0.74
OWV	3.68 ± 1.79
MOp	8.85 ± 1.86
MDe	12.12 ± 2.32
EuP	5.79† ± 1.35¶
PiP	9.51† ± 1.71¶

3.3 Soil organic carbon stocks

The mean SOC stock varied between 41.29 Mg ha^{-1} recorded from other woody vegetation and 30.10 Mg ha^{-1} recorded from open miombo. The highest (97.17 Mg ha^{-1}) and lowest (8.05 Mg ha^{-1}) value observed placed respectively on the same two LUCs. The mean stock of open miombo placed low compared to the five other LUCs, which had mean stock figures relatively close to each other. Results for all LUCs are shown in Table 9, and the stock distributions are visualized as box-and-whisker plots in Figure 23. Histograms for the SOC results are attached in Annex 2.

The median stocks and ranges of the SOC were relatively similar between the LUCs, except those of open miombo (Figure 23). Open miombo differentiated from all the others, having generally lower values and notably high S.D. (Figure 23, Table 9). However, the differences were not statistically significant.

Table 9. Mean soil organic carbon stocks. All results are shown as Mg ha^{-1} with S.D. included. Land use classes: FaL = Fallow land, OWV = Other woody vegetation, MOp = Open miombo, MDe = Dense miombo, EuP = Eucalypt plantation, PiP = Pine plantation.

LUC	SOC
FaL	38.92 ± 10.49
OWV	42.24 ± 14.56
MOp	31.49 ± 16.79
MDe	37.03 ± 10.63
EuP	36.02 ± 10.16
PiP	36.45 ± 10.83

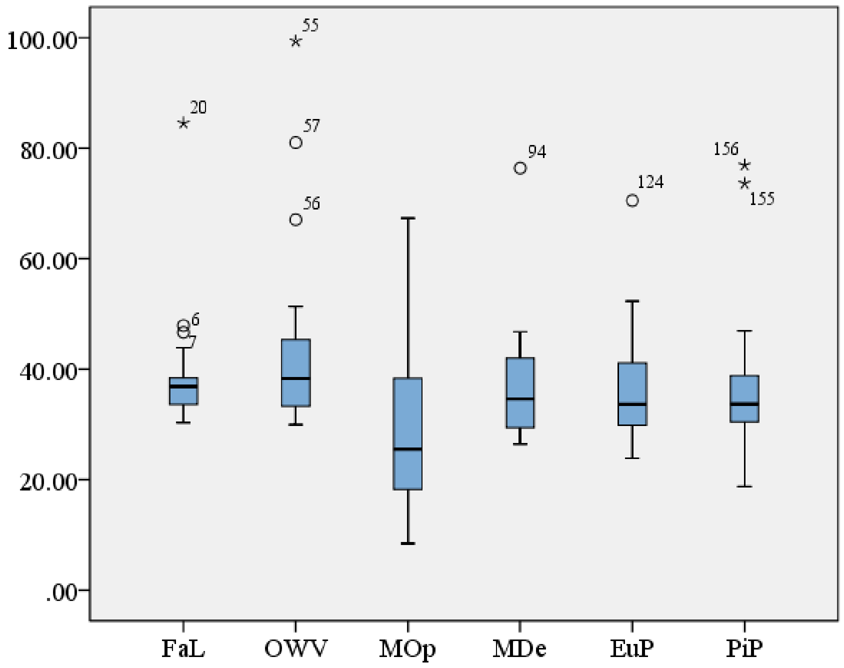

Figure 23. Box-and-whisker plots for soil organic carbon stocks. The values at y-axis are given as Mg ha^{-1}. The boxes represent observations between 25^{th} and 75^{th} percentile. The whiskers represent minimum and maximum values up to a limit of 1.5 times the height of the box. Observations beyond this point are considered outliers and marked as circles. Asterisks mark outliers further than three times the height of the box. Dark thick line represents the median value. Land use classes: FaL = Fallow land, OWV = Other woody vegetation, MOp = Open miombo, MDe = Dense miombo, EuP = Eucalypt plantation, PiP = Pine plantation. Figure drawn with SPSS.

Open miombo also demonstrated a distribution very different from the other classes (Figure 23, Annex 2). Histograms (Annex 2) show that the results of open miombo were close to continuous uniform distribution, while the other LUCs followed normal distribution tolerably, however being skewed to the right due data outliers.

The 12 soil samples that were measured as duplicates had an R squared value of 0.968 between the two groups. X-Y scatterplot of the data is presented in Annex 3, together with the BD results.

3.4 Total carbon stocks of the six land use classes

Combining all the sub-stocks covered above, the ecosystem mean total carbon stock between the different LUCs was found to vary between 42.59 Mg ha^{-1} and 86.81 Mg ha^{-1}. Fallow land represented the lowest figure and dense miombo the highest. The results are shown in Figure 24.

The ranking from smallest to largest C stock remained the same between the LUCs also after inclusion of the belowground C sub-stocks. However, the steepness (relative differences between the LUCs) was mitigated due introduction of the SOC results, which were distributed more equally between the LUCs than vegetation C as described in sections above. Figure 24 presents clearly how SOC accounted for the vast majority of the fallow land total C stock.

The numeric values for the bars of the Figure 24 with S.D. included are provided in a C stock compilation table in Annex 4. The annexed table compiles the results of all the C sub-stocks and total stocks recorded in this study.

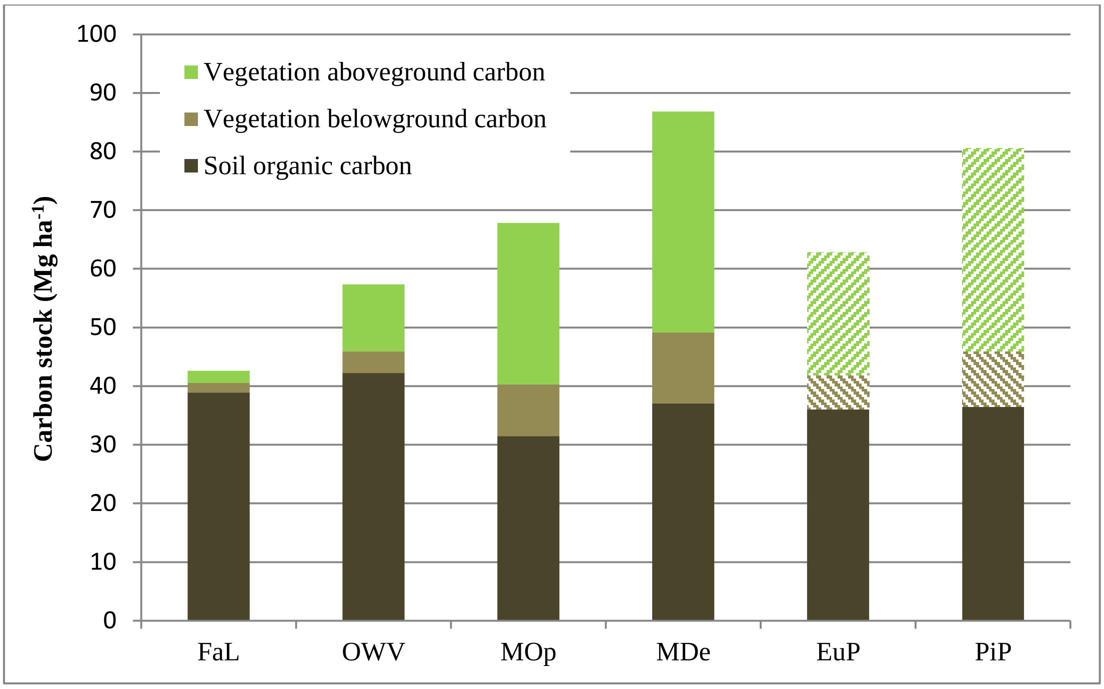

Figure 24. Mean total carbon stocks for the six land use classes of the study. Striped bars in EuP and PiP vegetation C stocks mark that they have a model-based estimate as a component. Other figures are based on calculated arithmetic means of the measured data. Land use classes: FaL = Fallow land, OWV = Other woody vegetation, MOp = Open miombo, MDe = Dense miombo, EuP = Eucalypt plantation, PiP = Pine plantation.

4. DISCUSSION

4.1 Comparison to other studies

4.1.1 Vegetation carbon stocks

Vegetation aboveground

The vegetation aboveground carbon stocks recorded for miombo woodlands in this study matched the range of pre-existing results. The values for open miombo (27.47 Mg ha^{-1}) and dense miombo (37.65 Mg ha^{-1}) come relatively close in matching the values suggested by Frost (1996) for drier and wetter miombo woodland (26 and 42 Mg ha^{-1} respectively), even though field observations indicate that the primary cause of the lower canopy coverage of open miombo in this study is BM removal by humans rather than climatic reasons. Dense miombo remains somewhat further from matching the correspondent, higher Frost (1996) value than open miombo.

Similarly, the relatively high aboveground C stock range (41–46 Mg ha^{-1}) reported by Timberlake et al. (2010) exceeds the dense miombo results of this study, however not substantially. Values matching or exceeding the range were also recorded in this study (4 out of 13 plots), even though the mean remained lower.

The woodlands measured by Sitoe et al. (2009) in Manica province, Mozambique, were classified as open miombo according to the same criteria than applied in this study. Their result 26.48 Mg ha^{-1} is almost identical with the 27.47 Mg ha^{-1} open miombo result of this study.

Ribeiro et al. (2008a) defined the criteria between classification to high and medium density woodland being canopy crown cover of above or below 50 %. Their result of 19.5 Mg ha^{-1} for the medium density woodland derived in Niassa Reserve remains significantly under the open miombo result by this study, even if the higher canopy cover was applied and the study sites are located relatively close to each other. The reason might be in different methodology in canopy cover determination (remote sensing data versus visual determination in ground). Their result for dense woodlands (35 Mg ha^{-1}) however is well consistent with the dense miombo result of this study.

Notably a number of other studies featured in Table 1 also resulted in lower C stocks for miombo woodlands than this study. This strengthens the indication of wide spatial variability in C stocks of miombo woodlands, caused by both natural (climatic and disturbance) and anthropogenic factors, and speaks for the importance of site and land cover class specific results.

Fallow land and other woody vegetation are tricky LUCs to compare with other studies because of a wide variety of different definitions that concern the classes – especially the latter. Kalaba et al. (2013b) measured mean aboveground C stocks for miombo vegetation re-growing after intense charcoal harvest. Their measurement areas of early to mid-stages of post-disturbance succession can be held comparable with the other woody vegetation LUC of this study. Their results for tree aboveground C stocks averaged 10.5 Mg ha^{-1} 10 years after abandonment and 19.2 Mg ha^{-1} 20 years after abandonment. While the latter C stock indicates an ascent into secondary miombo already, the former C stock matches well the 11.41 Mg ha^{-1} recorded for other woody vegetation in this study.

Comparison of the tree C stocks of the forest plantation LUCs to pre-existing figures is irrelevant in this context, since the results are derived using study-based models and dependable of the applied growing schemes.

Chidumayo & Kwibisa (2003) measured 20–50 % increase in grass BM on re-growing secondary miombo in comparison to non-cleared mature miombo sites. Surprisingly, the herbaceous vegetation C stocks measured in this study appeared independent of the vegetation cover (realized as different LUCs), since no statistical differences were detected between any of the classes.

The recorded shrub & sapling C stocks are difficult to compare with other existing results because of the varying definitions of the correspondent sub-stocks in other studies. Ryan et al. (2011) followed a well comparable methodology (DBH below 5.0 cm) on miombo woodlands, resulting in mean C stock of 1.1 Mg ha^{-1}. The figure is somewhat higher than what was recorded on miombo LUCs of this study.

However, it is not defined whether they only addressed saplings of trees or woody shrubs as well.

Litter and dead wood were excluded from the scope of this study, so their contribution to the C stocks of the measured plots remains unknown. Based on previous studies (Ribeiro et al. 2013; Woollen et al. 2012; Frost 1996) it can be assumed that the carbon stock of litter would have made up a maximum of 2 Mg ha^{-1} on plots representing miombo LUCs, but probably less. For the dead wood, giving a reliable estimate is not possible based on existing knowledge. The areas measured had not been subject to any major disturbance – excluding the ones caused by humans, which generally included removal of the harvested wood from site. No significant amount of dead wood was encountered at any of the sample plots included in this study, but this is a subjective observation rather than any real inventory result.

Vegetation belowground

The vegetation belowground C stocks are commonly derived by applying a pre-existing R:S ratio or allometric model to aboveground inventory results – exactly as was the case with this study. For example, Sitoe et al. (2009) applied a belowground BM equation presented by Pearson et al. (2005) to their inventory data, resulting in tree belowground C stock of 6.49 Mg ha^{-1} for open miombo. The relative difference between their result and the one of this study (8.85 Mg ha^{-1}) is larger than the difference between the respective aboveground C stocks due the different allometrics applied. Hence, the comparison between results derived with this methodology is of low relevance herein.

The previous statement excludes studies that have developed a new, site-specific ratio or model, on which their belowground C stock estimate is based. Such studies were conducted in miombo by Chidumayo (2013a), Ryan et al (2011) and Malimbwi et al. (1994). The reported C stock results varied widely: 13.7 Mg ha^{-1}, 8.5 Mg ha^{-1} and 2.0 Mg ha^{-1}, respectively (assuming C content of 0.47 in BM). The two former figures match quite well what was calculated respectively for dense and open miombo in this study. The last figure is closer to what was calculated for other woody vegetation and fallow land. The explanation for low result by Malimbwi et al. (1994) is both the low R:S ratio derived in the study and apparently degraded structure of the miombo aboveground vegetation, as implied by the paper.

4.1.2 Soil organic carbon

One of the key findings of this study was that SOC did not behave as it was expected to between the LUCs. The expectation was that LUC has an effect on the SOC stock. A number of pre-existing studies demonstrate that the SOC content is dependable of the vegetation cover above, and especially occurrence of woody vegetation, on savannas and woodlands of sub-Saharan Africa (Saiz et al. 2012; Rossi et al. 2009; Wang et al. 2009; Bird et al. 2004) as well as globally in general (Post & Kwon 2000). Walker & Desanker (2004) reported significant difference in SOC of non-degraded miombo in comparison to agricultural and fallow lands, which demonstrated 47 and 44 % less C respectively. A meta-analysis by Guo & Gifford (2002) addressing SOC dynamics related to land use changes in life zones from tropical to temperate indicates a mean 42 % decrease upon conversion from native forest to cropland. Sombroek et al. (1993) suggest a correspondent SOC decrease of up to 50 % for topsoil, while noting that the deeper layers may remain relatively unaffected.

Same phenomenon has been recorded with conversion to plantations. The Guo & Gifford (2002) analysis indicates a 13 % mean decrease in SOC stocks upon conversion from native forest to plantation. In tropical evergreen forests of Kenya, a decrease of circa 30 and 45 % of SOC occurred when the indigenous forests were compared to eucalypt and pine plantations replacing them, respectively (Omoro et al. 2013). In Ghana, a decrease of 28–61 % of SOC in topsoil occurred in conversion of indigenous forests to a variety of NWFP plantations (Chiti et al. 2014). Also on miombo a statistically significant decrease (10 %) in SOC between the indigenous woodlands and pine plantations has been measured (King & Campbell 1994).

Chidumayo & Kwibisa (2003) found evidence of organic matter decrease in miombo topsoil also as a result of forest degradation, although the differences were not statistically significant.

Given the figures above, it was reasonable to expect detectable differences in SOC mean stocks recorded this study. Hence it was a surprising result that no statistically significant differences were found between the LUCs, even though the distributions were of different shape. Fallow land did not show evidence of SOC decrease in comparison to miombo LUCs, and neither did plantations. There are at least two possible explanations for the result. One is that the time since the land use conversion from miombo to other LUCs took place on the sampling areas is so limited, that the changes in soil cannot be detected yet. Another is that the SOC stock is mainly dependable of the soil properties and only to limited extent of the vegetation. Both of these may apply in the case of this study.

The time hypothesis can be addressed by looking back to the land cover history of the studied sites. Unfortunately, there is little high-resolution data available to address this purpose. Deforestation maps of the area based on remote sensing have been presented by Global Forest Change map (published by Hansen et al. 2013) and Dobbin International (2013). The data by Hansen et al. (2013) does not show appreciable changes in the forest cover considering the measurement areas in 2000–2012, suggesting that the land use conversion from miombo woodlands have occurred more than a decade prior to the field measurements of this study. The data by Dobbin International (2013) is not of equally high resolution, but extends further back in time. A careful conclusion that detectable forest cover loss has occurred at least on measurement areas D and F since 1990 can be made based on the data. On the contrary, measurement sites for all of the forest plantations and area A (fallow land) show no sign of pre-existing forest cover neither during this observation period.

Little is known about the SOC dynamics of miombo woodlands, especially concerning decomposition rates belowground. No long-term follow-up studies on coarse woody debris decomposition were discovered in the course of this study. Mapanda et al. (2013) surveyed agricultural lands four years after clearance from miombo, and found out that the changes in soil chemical properties had not necessarily been reflected into lowered SOC stocks. Vice versa, Williams et al. (2008) found evidence of very slow SOC accumulation in secondary miombo woodlands up to 30 years of age, previously under agricultural use. If the soil processes are as slow as the results above indicate, it is likely that the results of this study are at least partially explained by the limited time frame.

There is also evidence that age is a complicated factor when it comes to explaining SOC stocks related to forested land use types in the tropics. While many studies recognize the effect of land use age on SOC (e.g. Chiti et al. 2014), a pantropical meta-analysis by Marín-Spiotta & Sharma (2013) found that age of secondary forests and plantations only explained the SOC quantities to limited extent, if at all. It has been shown that climate and soil structure (with clay mineralogy especially) also have critical effect on SOC quantities in relation to land use changes, through processes of C stabilization – which may either appear strong on a site or not, depending very much of the given factors (Powers et al. 2011; López-Ulloa et al. 2005). Powers et al. (2011) also point out that these processes are not thoroughly and representatively studied in dry tropical landscapes.

In any case, the divergent (though statistically not significant) result for open miombo cannot be explained by the time factor, since a notable forest cover was present on the measurement area (despite of the ongoing degradation). Instead, the properties of the soil are more likely to be the underlying reason. The different soil color (grey) observed in area B, the primary measurement area for open miombo, also indicates different soil properties in comparison to other measurement areas (generally demonstrating red color). However, assessment of soil properties other than the C content was not included in the scope of this study, and hence further investigation would be needed.

It should also be recognized that SOC stocks of pristine miombo woodlands have demonstrated highly irregular behavior between sample sites in other studies. Both Ryan et al. (2011) and Williams et al. (2008) resulted in non-normal distribution of the miombo SOC stock results, divided across a wide range. The results from Ryan et al. (2011) demonstrate almost uniform distribution from 32 to 133 Mg ha^{-1}. It is acknowledged by both studies that estimating the mean for miombo SOC stocks is problematic because of the shape of the distribution. The same phenomenon was encountered in this study.

The results of this study concerning SOC stocks of the dense miombo did not provide surprises. The average stock measured from dense miombo topsoil matched very well the 40.1 Mg ha^{-1} reported by Woollen et al. (2012). The figure is somewhat exceeded by results from Ryan et al. (2011) and Walker & Desanker (2004), with 41.7 and 40.0 Mg ha^{-1} respectively in the top 20 cm only. The topsoil results from Williams et al. (2008) were significantly higher (a median of 57.9 Mg ha^{-1}). The average stock measured from open miombo in this study appears low in comparison with the previous studies. However, arithmetic mean may not be a good statistical parameter to describe the SOC stocks considering both miombo LUCs. This is because the results were not normally distributed and especially open miombo had a very wide range between the minimum and the maximum observation (Annex 2). Yet applying e.g. median (Figure 23) will not change the outcome that the stocks were smaller in comparison with the pre-existing studies referred above.

4.2 Evaluation of the methodology applied

Land use classification and choice of the field sampling areas

While the land use and land cover classification presented by Marzoli (2007) in the IFN was way too wide and detailed as such for the needs of this study, the elements of the classification applied in this study are also present in his report. The classification of this study is also consistent with the one applied in the recent national forest inventory of Tanzania (NAFORMA) considering the main outlines (Vesa et al. 2010). Studies with comparable land use classification have been conducted at the faculty of agriculture and forestry engineering in UEM (Mavie 2012; Tomo 2012).

Considering the land use and land cover witnessed at the study site, the land use classification of this study covers the existing vegetation types well without major gaps – excluding that of the active agricultural land. The double definition between fallow land and other woody vegetation left some margin for different interpretations, but the choice of the measurement areas was originally conducted in such way that it did not affect the results.

Self-evidently, the choice of the measurement areas had an effect on the results. A great emphasis was put into choosing measurement areas that would represent their respective classes on average. However, since the procedure was not based on inventory, the subjective decisions added unknown bias to the quantified C stocks. Survey grid over the whole study site and random survey lines were both considered as methodology, but discarded as practically non-realizable in the complex landscape.

If the subject was to be studied further, it would be recommendable to survey each LUC on a number of sites. This was not conducted with two LUCs of this study: dense miombo and fallow land. Fallow land in the measurement area A had probably shorter fallow land periods on the average before re-conversion back to agriculture than the 0–5 years set by the LUC definition. This would suggest that the class aboveground C stock result was somewhat underestimated. However, given the big picture of the C stock allocation in the landscape, the effect can be held close to negligible. Based on the best knowledge available, the other measurement areas can be held as average representatives of their LUCs as possible.

Fire as a regular feature of the miombo landscape was realized also in the course of this study as a straight effect on the recorded C stock quantities. On fallow land and other woody vegetation sample areas, 7 out of 13 and 4 out of 17 plots respectively were found to be recently burned. The new herbaceous vegetation on these plots was typically emerging, but because of the late dry season the grasses were still tiny and juvenile. If the study would have been conducted with the full herbaceous vegetation cover present, higher average C stocks would have been most certainly recorded, especially for fallow land. Some outliers (55, 56, 58) featured in Figure 22a hint of possible quantities on other woody vegetation; all of them represent unburned sites.

Choice of allometric equation and determination of aboveground carbon

The choice of allometric equation has a significant effect on tree aboveground C stock results, and therefore locally derived or adjusted equations should always be used in the process (Pearson et al. 2005). There was a general lack of such equations concerning the site of this study (Henry et al. 2011). The equation (1) developed by Macia (unpublished) in the PAIMO project framework was considered the most reliable and locally adjusted equation available. The DBH range of the data behind the equation was 11.0–42.6 cm, which was considered sufficient in relation to the DBH range of the trees recorded in this study (5.0–52.5 cm). The species composition was also assumed to be comparable since the equation data was derived from similar woodlands at the study site with all the main species represented, though the comparability could not be ensured.

The measurement of trees carried within typical sources of error. The form of the tree species of the native vegetation presented some special challenges. The practice of recording trees branched below 1.3 m as separate individuals is likely to result in a slight overestimation of BM. The unavoidable error resulting from hypsometer in height measurement (primarily from determination of the treetop) was addressed by using the 20 m distance whenever possible instead of the 15 m, out of the two standard distances provided. At older-class pine plantations the height measurement with hypsometer was most convenient. However, certainly the most accurate height results were derived by pole with the short trees.

It remains unknown how applicable the 0.25 conversion factor from fresh mass to carbon was considering the small-diameter miombo vegetation and woody shrubs on which it was applied. No data describing specifically the moisture content of miombo woody species was found. Even if such data would have been available, it would barely have brought any added value: the sampled woody vegetation was very heterogeneous in terms of both species and structure, so it would have been necessary to use some average factor anyway.

A significantly larger shrub & sapling C stock was recorded on other woody vegetation compared to the other LUCs of this study. This was because of the small diameters of the re-growing miombo vegetation, which the plots of the LUC typically represented. Stem count often included lots of sprouts, many of which remained under the 5.0 cm DBH, and hence did not match the definition of tree. Comparison of the shrub & sapling C stock quantity of this class to other studies is especially difficult, since the shrub & sapling C stock is highly definition-sensitive. Since on majority of the other LUCs shrubs & saplings did not contribute significantly to the total C stock (excluding fallow land herein), it might have been both reasonable and more efficient to exclude it from the survey as a sub-stock and lower the minimum definition of tree instead. This has been applied in some other studies, for example by Chidumayo (2013b). However, this requires models applicable for small-diameter trees.

Determination of root to shoot ratio

The belowground C results were dependable of the applied R:S ratios. Ratios presented by Mokany et al. (2006) were chosen because of the wide data basis of their study. Their ratios are also behind the most of the correspondent IPCC (2006) recommendations. There were two relevant ratio figures to choose from: “Tropical/subtropical dry forest/plantation” and “Tropical/subtropical/temperate woodland”, valued 0.275 and 0.322 respectively. The latter figure was considered to represent miombo better by definition, and the decision to choose a higher ratio was also supported by site-specific studies on miombo by (Chidumayo 2013a) and (Ryan et al. 2011). The former figure was applied in the case of forest plantations. A different figure between the LUC groups was used because forested land covers in the tropics tend to have R:S ratios smaller than savannas and woodlands (Mokany et al. 2006; IPCC 2006, 2003).

The decision about the applied R:S ratios was not self-evident. For example Sitoe et al. (2009) used a belowground BM model that gave results a little below the former figure (0.275) under comparable circumstances. Then again significantly higher ratios (around 0.5) have been presented (Chidumayo 2013a; Ryan et al. 2011). Concerning forest plantations, it has been shown with eucalypt that the R:S ratio is e.g. dependable of the amount of water available (Barton & Montagu 2006).

With the limited knowledge available, it has to be recognized that the belowground C stock estimation of this study is a generalization that includes major uncertainty. This is especially true with the forest plantation LUCs, since already their aboveground stocks are projected figures. However, at the very least the results provide a reasonable estimate of the magnitude of the vegetation belowground C stocks.

Limitations of soil sampling depth and reliability of the analysis

The SOC survey was limited to the topsoil only. What quantities the C stocks were under the depth of 30 cm and how they would have affected the comparison between the LUCs remains a subject of speculation. Walker & Desanker (2004), addressing SOC stocks down to 150 cm, found that about 54 % of SOC stock was under the depth of 20 cm and still 37 % was under the depth of 40 cm. Considering these figures, a rough estimate for the SOC stocks down to 150 cm at the dense miombo sampled in this study would be 60–80 Mg ha^{-1}.

Soil sample analysis was found to be fairly precise. The 12 randomly picked samples that were measured as duplicates demonstrated strong linear regression with R squared value of 0.968. This indicates that the unexpected SOC result between the LUCs cannot be explained by methods of analysis, and also testifies for relatively homogenous soil material included in the samples. Yet, it is possible that some of the outliers in the SOC results with high value (Figure 23 and Annex 2) are due unintentional inclusion of organic material particles – the analysis is sensitive for even tiny fractions of organic material, since a very small amount of soil (< 1 g) is featured in the analyzed samples. The high results may also simply indicate a wide natural variation in miombo SOC, which has been featured in the results by Ryan et al. (2011) and Williams et al. (2008).

Plantation growth estimation

Plantation growth estimation represented the weak point of this study, which is hardly uncommon for studies including modelled components. The variation of the data was lost due taking the step from the average site index to the corresponding mean annual yield. This made it impossible to do valid statistical analysis between forest plantation LUCs and native vegetation LUCs. An alternative approach would be modelling growth for each individual sample plot. However, this requires that applicable and highly reliable models are available in order to provide added value to a study.

It is probable that the presently juvenile eucalypts will demonstrate better growth in the future than what was measured and estimated in this study. This is because older eucalypts (8,6 years) were only measured on a single stand, the only one present at the study site, which demonstrated poorer growth than what was estimated as the potential by the company. The reason for this was that the site indices under the circumstances of the study site are dependable of forest management activities, primarily soil preparation and fertilization. The stand was too old that these practices would have been effectively in use by the company already by the time when the planting took place. Because of similar reasons, two age groups of pines demonstrated poor growth and were excluded from the site quality index determination.

5. CONCLUSIONS

Carbon stocks of six different land use classes in Niassa province of northern Mozambique were quantified in this study. The LUCs included native vegetation (miombo woodlands) of both pristine state and modified by traditional land use, as well as industrial forest plantations emerging at the study site. The quantified total C stocks for miombo woodlands and related transitional vegetation made sense in the light of previous studies. Soil organic carbon stocks had an unexpected result of not demonstrating any statistically significant differences between the LUCs.

The research questions of the study could be answered through the results of the inventory and calculations conducted. Addressing the study hypotheses was more uncertain. No statistically significant differences were detected considering SOC between the plantation LUCs and the native vegetation LUCs. Since statistical analysis between the total aboveground C stocks was impossible between the two LUC groups, limited conclusions can be driven from the results. The aboveground C stocks of the forest plantation LUCs were found to be of the same order of magnitude with the correspondent stocks of the LUCs representing miombo woodlands. Especially when paired as open miombo – eucalypt plantations and dense miombo – pine plantations, no significant difference between these LUCs could safely be declared, given the distribution parameters (S.D., both calculated and estimated) and the uncertain nature of modelling. Comparison limited to these classes supports the hypothesis H0. On the contrary, when the two other native vegetation LUCs (fallow land and other woody vegetation) were also taken into account, the difference between their aboveground C stocks compared to those of the plantation LUCs showed differences so wide that even with the given uncertainty they could be held significant. It is also reasonable to expect that the new generation of eucalypt stands will perform better in growth and yield, increasing the gap. Based on this latter comparison, there is evidence to discard the hypothesis H0.

This study provides a better understanding about the quantities related to C stock dynamics in the miombo landscape, widely subjected to transition by anthropogenic drivers, with a particular reference to northern Mozambique.

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ANNEX 1: Ground photos of the land use classes

ANNEX 1.1. Dense miombo. Photo taken at measurement area C. New leaves are emerging after dry season, occurring in different shades of red, yellow and green.

ANNEX 1.2. Open miombo. Photo taken at measurement area B.

ANNEX 1.3. Other woody vegetation. Photo taken at measurement area D.

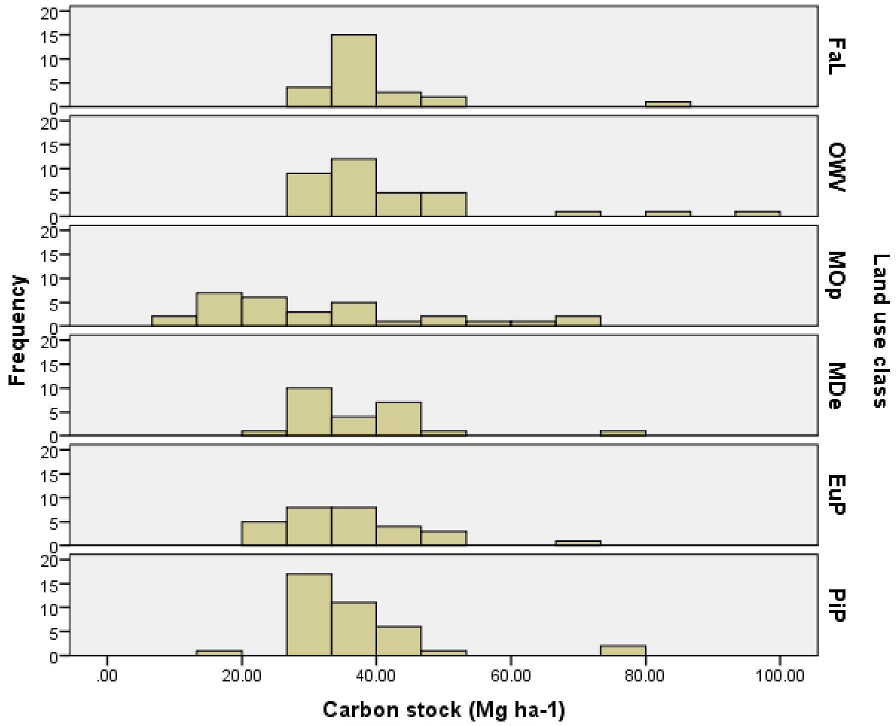
ANNEX 1.4. Fallow land. Photo taken at measurement area A.

ANNEX 1.5. Eucalypt plantations. Photo taken at 0.6 years old *Eucalyptus urograndis* stand.

ANNEX 1.6. Pine plantations. Photo taken at 4.7 years old *Pinus maximinoi* stand.

All photos in Annex 1 are by Arttu Pienimäki.

ANNEX 2: Soil organic carbon stock histograms

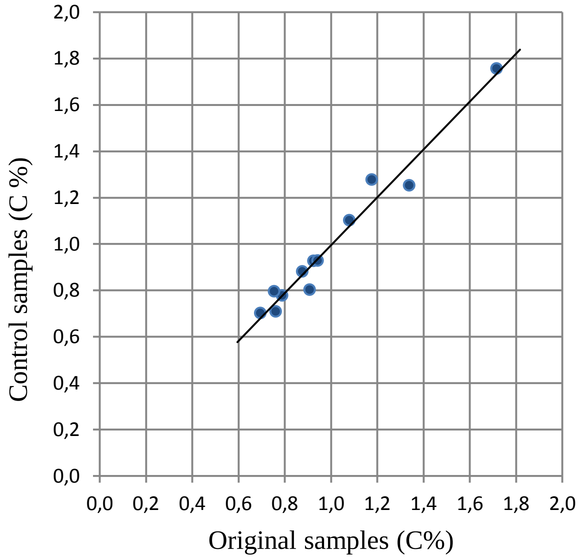


ANNEX 2: Histograms of the soil organic carbon (SOC) stock results. Land use classes: FaL = Fallow land, OWV = Other woody vegetation, MOp = Open miombo, MDe = Dense miombo, EuP = Eucalypt plantation, PiP = Pine plantation. Figure drawn with SPSS.

ANNEX 3: Bulk density and duplicate analysis

ANNEX 3.1. Results for bulk density (BD) with standard deviation attached. All values are kg m^{-3}. Land use classes: FaL = Fallow land, OWV = Other woody vegetation, MOp = Open miombo, MDe = Dense miombo, EuP = Eucalypt plantation, PiP = Pine plantation.

LUC	BD
FaL	1161.6 ± 77.2
OWV	1329.8 ± 108.8
MOp	1299.8 ± 47.2
MDe	1242.6 ± 97.0
EuP	1262.0 ± 43.8
PiP	1223.8 ± 47.2



ANNEX 3.2. X-Y scatterplot of the soil samples measured as duplicates (n=12). R squared = 0.968.

ANNEX 4: Carbon stock compilation table

All results are given as $Mg\ ha^{-1}$ with S.D. included. † The figure is a model-based estimate, or has a model-based estimate as a component. ¶ The figure has been estimated based on tree height distribution data. Distribution estimate cannot be calculated for EuP and PiP grand totals, because they include variation from two components (SOC and estimated). SOC = Soil organic carbon. Land use classes (LUCs): FaL = Fallow land, OWV = Other woody vegetation, MOp = Open miombo, MDe = Dense miombo, EuP = Eucalypt plantation, PiP = Pine plantation.

LUC	Vegetation C						SOC	Grand Total
	Aboveground C				Belowground C	Vegetation Total		
	Trees	Shrubs & saplings	Herbaceous	Aboveground Total				
FaL	0.30 ± 0.66	1.11 ± 0.94	0.63 ± 0.36	2.04 ± 1.14	1.63 ± 0.74	3.67 ± 1.73	38.92 ± 10.49	42.59 ± 7.89
OWV	8.08 ± 4.82	2.75 ± 2.41	0.59 ± 0.78	11.41 ± 5.55	3.68 ± 1.79	15.09 ± 7.34	42.25 ± 14.56	57.33 ± 14.55
MOp	25.74 ± 6.35	0.72 ± 1.27	1.02 ± 0.55	27.47 ± 5.77	8.85 ± 1.86	36.32 ± 7.63	31.49 ± 16.79	67.81 ± 17.09
MDe	36.41 ± 7.11	0.56 ± 0.50	0.68 ± 0.29	37.65 ± 7.20	12.12 ± 2.32	49.78 ± 9.52	37.03 ± 10.64	86.81 ± 18.91
EuP	20.24[†] ± 4.71[¶]	0.27 ± 0.36	0.54 ± 0.52	21.04[†] ± 4.90[¶]	5.79[†] ± 1.35[¶]	26.83[†] ± 6.24[¶]	36.02 ± 10.16	62.85[†]
PiP	33.00[†] ± 5. 92[¶]	0.48 ± 0.54	1.11 ± 1.32	34.59[†] ± 6.21[¶]	9.51[†] ± 1.71[¶]	44.10[†] ± 7.91[¶]	36.45 ± 10.83	80.55[†]