LAND COVER DYNAMICS AND ESTIMATES OF VOLUME AND BIOMASS OF THICKET AND TREE SPECIES IN ITIGI THICKET, TANZANIA

JOSEPH SITIMA MAKERO

A THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY OF THE SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

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EXTENDED ABSTRACT

The study was carried out in Itigi thicket in Manyoni District to assess land cover dynamics and estimate biomass and volume of thicket and tree (*associate trees*) species. The assessment of land cover dynamics was based on data extracted from remote sensing using the 1991, 2000 and 2011 satellite images and key informants interviews. The estimation of biomass and volume of thicket and tree species, data from destructive and non-destructive sampling was used. Sixty thicket clumps and thirty trees were sampled for destructive sampling. The study covered two dominant thicket species: *Combretum celastroides* Laws and *Pseudoprosopsis fischeri* (Tab) Harms and five dominant tree species: *Canthium burtii* Bullock sensu R. B. Drumm, *Cassipourea mollis* (R. E. Fr.) Alston, *Haplocoelum foliolosum* L, *Lannea fulva* (Engl.) England and *Vangueria madagascariensis* J. F. Gmelin. All sampled thicket clumps and trees were destructively for above- (AGB), belowground (BGB) biomass and volume. Analysis of land cover dynamics was based on supervised image classification using maximum likelihood classifier (MLC). For modelling biomass and volume of individual thicket clump and tree, different nonlinear multiplicative model forms were tested. The final models of biomass were selected based on Akaike Information Criterion (AIC) while the final models of volume were selected based on coefficient of determination (R^2) and relative root mean square error (RMSEr). Then the final selected models were applied to estimate biomass and volume of non-destructive sampling data. The results showed that thicket occupies large area in Itigi thicket. For example in 1991, the area occupied by thicket was 345 150.5 ha (67.85 %), in 2000 was 313 451 ha (61.62 %) and in 2011 was 293 444.8 ha (57.7 %). Apparently, this large area occupied by thicket declined during 1991 - 2000 and 2000 - 2011. The decline in thicket areas was attributed to increase in anthropogenic activities such as wood extraction, clearing for agriculture, livestock grazing and fires. The model fitting showed that, large parts of the variation in biomass of thicket clumps were explained by basal area weighed mean diameter at breast height (dbh_w) of stems in the clump and number of stems in the clump (stem count, i.e. st), i.e. for AGB and BGB of *C. celastroides* Laws up to 89 % and 82 % respectively and for AGB and BGB of *P. fischeri* (Tab) Harms up to 96 % and 95 % respectively. For tree species most variation was explained by diameter at breast height (dbh) alone, i.e. up to 85 % and 69 % for ABG and BGB respectively. It was also noted that, for thicket, large parts of the variation in volume of thicket clumps were explained by dbh_w, height (ht) and stem count, i.e. for *C. celastroides* Laws up to 69 % (R^2) and for *P. fischeri* (Tab) Harms up to 93 %. For trees most variation was explained by dbh and ht, i.e. up to 93 %. Although there might be some uncertainties related to biomass and volume estimates for large areas, for practical reasons, it is recommended the selected models to be applied to the entire area where Itigi thicket extends outside the study site, and also to those thicket and tree species present that were not included in the data used for modelling. The methods used in this study to assess land cover dynamics, biomass and volume stocks of thicket and tree species highlight the importance of integrating remote sensing and forest inventory in understanding the thicket resources dynamics and generating information that could be used to overcome the Itigi thicket problems for the sustainability of this unique vegetation.

THESIS ORGANIZATION

This thesis begins with an extended abstract followed by thesis organization, declaration statement, copyright statement, acknowledgements, dedication, table of contents, list of papers and declaration of the paper, list of tables, list of figures, list of appendices, list of abbreviations and acronyms. The extended abstract summarises the study objectives, approaches to sampling, results and discussion, conclusions and recommendations. The thesis also consists of six chapters. The first chapter covers introduction which includes, background information, problem statement and justification, study objective, research questions and conceptual and theoretical frame work. The second chapter covers literature review. Chapter three includes methodology which provides descriptions of the study area, sampling, and data analysis. Chapter four presents results and discussion of the study and chapter five covers conclusions and recommendations. Chapter six contains a series of original published papers (*Paper 1, Paper 2* and *Paper 3*) and publishable manuscripts (*Paper 4*).

DECLARATION

I, JOSEPH SITIMA MAKERO, do hereby declare to the Senate of Sokoine University of Agriculture that, this thesis is my own original work, done within the period of registration and that it has neither been submitted nor being currently submitted in any other Institution.

____________________________ ____________________

Joseph Sitima Makero Date

(PhD Candidate)

The above declaration is confirmed by:

____________________________ ____________________

Prof. R.E. Malimbwi Date

(Supervisor)

____________________________ ____________________

Prof. E. Zahabu Date

(Supervisor)

____________________________ ____________________

Prof. J.J. Kashaigili Date

(Supervisor)

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DEDICATION

This work is dedicated to God almighty, my wife Winfrida, daughters, Jackline and Glory, sons, Johnson, Wilson and Harrison, to my father, Justine and mother, Opportuna.

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LIST OF PAPERS

Paper 1: Makero, J.S., and Kashaigili, J.J., (2016). Analysis of Land-Cover Changes and Anthropogenic Activities in Itigi Thicket, Tanzania. *Advances in Remote Sensing* 5:269 - 283

Paper 2: Makero, J.S., Malimbwi, R.E., Eid T. and Zahabu, E. (2016).Models predicting above- and belowground biomass of thicket and associate tree species in Itigi thicket vegetation of Tanzania. *Agriculture, Forestry and Fisheries* 5(4): 115 - 125.

Paper 3: Makero, J.S., Malimbwi, R.E., Zahabu, E. and Eid T. (2016).Models for prediction of volume of thicket and associate tree species in Itigi thicket vegetation of Tanzania. *Journal of Forestry* 3: 1 - 15.

Paper 4: Makero, J.S., Zahabu, E. and Malimbwi, R.E. Estimation of volume and biomass of thicket and tree species in Itigi thicket, Tanzania. *Manuscript* (Ready for submission)

DECLARATION OF THE PAPERS

I, Joseph Sitima Makero, do hereby declare to the Senate of Sokoine University of Agriculture that the above listed papers comprising this thesis summarise my independent efforts and they constitute my own original work and they will not be part of another thesis in any other University.

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LIST OF ABBREVIATIONS AND ACRONYMS

AGB	Aboveground biomass
AIC	Akaike Information Criterion
BGB	Belowground biomass
Dbh	Diameter at breast height
Dbh_w	Basal area weighed mean diameter at breast height of stems
FAO	Food and Agriculture Organisation of the United Nations
GIS	Geographic Information System
GPS	Global Positioning System
Ht	Total height of tallest stem
MPE_r	Relative Mean Prediction Error
R^2	Coefficient of determination
RMSE	Root Mean Squared Error
RS	Mean Root Square-ratios
St	Stem count
STD	Standard deviations
STDr	Relative standard deviations
URT	United Republic of Tanzania
WWF	World Wildlife Fund for Nature

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information

Thicket is a low forest consisting of a closed stand of bushes and climbers between 3 and 7 m tall (White, 1983) and is generally influenced by soil type and structure (FAO, 2000). In south-eastern Africa, thicket has a discontinuous distribution in the Zambezian region and occurs in Tanzania (Singida and Dodoma regions), Zambia (in the depressions between Lake Mweru and the southern end of Lake Tanganyika) and a few localities in the Democratic Republic of Congo (White, 1983; WWF, 2014). In Tanzania and Zambia, it covers a total area of about 7800 km^2. The climate of the thicket's core area is semi-arid to sub-humid (rainfall 250 - 800 mm per year) and subtropical to warm-temperate (largely frost-free). Thicket vegetation has woody flora of about 100 species (Kindt *et al.*, 2011) and it is dominated by trees and shrubs (Cowling *et al.*, 2005).

In Tanzania, a large part of thicket vegetation is in Manyoni District and it is named Itigi thicket (named from Itigi town in Manyoni District). Itigi thicket extends from Manyoni District to Singida Rural District and Bahi District in Dodoma region and is endemic to these areas. Itigi thicket covers an area of about 410 000 ha (URT, 2008). This vegetation type is unique in its occurrence, earmarked as ecologically sensitive for conservation (WWF, 2014). A recent sample plot inventory in the area showed that *Pseudoprosopsis fischeri* (Tab) Harms and *Combretum celastroides* Laws contribute more than 50 % of all stems, biomass and volume of wood species (unpublished results, *Paper 4*).

Itigi thicket plays an important role to community surrounding them by supplying bee products, livestock feeds, mushrooms, timber and medicinal plants. Itigi thicket is very significant for harbouring many game birds, small browsers, and larger animals such as elephants (WWF, 2014).

Although Itigi thicket is essential for the survival of humankind and wild animals, it has been threatened by an array of anthropogenic activities, because of its complex and fragile ecosystems. The vegetation type is considered endangered with about 50 % of it in Tanzania and as much as 71 % in Zambia having been cleared; apparently clearing takes place even in protected areas (Almond, 2000 in WWF, 2014). Turner *et al.* (1994) and Lambin *et al.* (2003) pointed out that, anthropogenic activities have transformed the earth's surface by converting natural forests, savannas and steppes into agricultural lands and substantially modifying others with significant consequences for land cover, biodiversity, soil condition, water and sediment flows. Land cover changes have accelerated in the 20th Century, both in pace and intensity, because of increased intensity of anthropogenic activities (Ramankutty *et al.*, 2006). Understanding the nature and extent of land cover changes as well as assessing the driving forces behind the change is essential for explaining the past and forecasting future patterns and in designing appropriate interventions (Di Gregorio *et al.*, 2005).

Initiatives to manage Itigi thicket in Tanzania exist, for example only 1 916.2 ha of Itigi thicket is protected (URT, 2008). National Forest Policy also promotes management of forest resources including thicket to improve both condition and livelihood (URT, 1998). Management planning of thicket is also important step towards achieving their sustainable management. Information on quantity and quality of thicket resources is an essential input in planning process.

Likely, there are global initiatives aiming at mitigating and adaptation on impacts of climate change. Such initiatives include REDD+ (Reducing Emissions from Deforestation and forest Degradation) (UNFCCC, 2011). REDD+ therefore offers an opportunity for conservation and management of forest including thicket. Successful implementation of REDD+ relies on routinely and reliably monitor changes of forest areas through establishment of a monitoring, reporting and verification (MRV) system (Hewson *et al.*, 2013).

Effective MRV system requires that carbon stocks and changes be done in consistent, complete and transparent. This should consider carbon pools; aboveground biomass (AGB), belowground biomass (BGB), dead wood, litter and organic soil carbon (IPCC, 2003).

Estimation of biomass and volume for Itigi thicket will help Tanzania to get benefits more from the global carbon mitigation strategies such as REDD+ and hopefully contribute to conservation and sustainable management of thicket vegetation.

1.2 Problem Statement and Justification

Information on biomass and volume stocks is important in order to support management of Itigi thicket. This information is also needed for sustainable planning of forest resources and for studies on the energy and nutrients flows in ecosystems. According to WWF (2014), Itigi thicket is under threat of being depleted due to anthropogenic activities which include; clearing land for agriculture and settlement, wildfires and cutting trees and thicket for fuel wood and charcoaling. These activities have greatly contributed to the change of Itigi thicket. According to Kideghesho (2001) in WWF (2014), Itigi thicket vegetation is removed by 50 % and the larger part of this area is still unprotected.

If the situation will remain the same, this vegetation will face total extinction between 2009 and 2019 (e.g. Almond, 2000 in WWF, 2014). To understand the magnitude and pattern of these changes, analysis of land cover changes using remotely sensed data and quantification of biomass and volume of thicket and tree species is very important.

According to Zhou *et al.* (2008), land cover change often reflects the most significant impact on the environment due to human activities or natural forces and that remote sensing can be an appropriate tool for getting wide impression on land cover change. The mid-resolution, multi-temporal satellite images such as Landsat, has been the most reliable source of data for monitoring forest change. These images provide encoded radiance data in the visible near-and middle-infrared spectra, in which most mature tropical forest can be spectrally distinguished from farm, fallow land and other non-forest vegetation (Sader *et al.,* 1991; Moran *et al*., 1994; Steininger *et al*., 1996; Steininger *et al.,* 2000).

Quantification of biomass and volume of wood stocks by using allometric models may be considered efficient and accurate. Allometric models are useful tools in assessing forest structure and conditions. They may provide information on supply of industrial wood, biomass for domestic energy and even on availability of animal fodder from the forest. In recent years, various biomass and volume models have been developed in sub-Saharan Africa. A review report describing such models from sub-Saharan Africa (Henry *et al.,* 2011) shows that biomass and volume models are unevenly distributed among vegetation types. While for example 43 % of the biomass models and 63 % of the volume models were developed for tropical rainforests, only 16 % of the biomass models and 23 % of the volume models were developed for shrub-land. In Tanzania, efforts to develop biomass and volume models for different forest types were on miombo woodlands; e.g. Malimbwi *et al.* (1994); Chamshama *et al.* (2004); Mugasha *et al.* (2013); Mauya *et al.* (2014) and on montane forests; Munishi *et al.* (2000); Masota *et al.* (2014).However, no efforts have been directed at developing models for thicket in Tanzania.

Since no study on land cover changes, biomass and volume of wood species reported, it was worthy to detailed assessment of land cover changes, biomass and volume of wood species in Itigi thicket. Therefore, the study aimed to assess land cover dynamics of Itigi thicket. Beside this, the study intended to develop biomass and volume models for estimating biomass and volume of thicket and tree (*associate trees*) species. The information on land cover dynamics, biomass and volume of thicket and tree species reported will help Tanzania to get benefits more from the global carbon mitigation strategies such as REDD+ and hopefully contribute to conservation and sustainable management of Itigi thicket vegetation.

1.3 Study Objectives

1.3.1 Main objective

The main objective of this study was to assess land cover dynamics and estimate biomass and volume of thicket and trees of Itigi thicket of Tanzania.

1.3.2 Specific objectives

To achieve the main objective, four specific objectives were addressed. Each specific objective comprised a full length paper. The objectives were:

1) To assess land cover changes in Itigi thicket for the periods; 1991, 2000 and 2011;
2) To develop allometric models for estimating above- and belowground biomass for thicket and trees;

3) To develop allometric models for estimating volume of thicket and trees;
4) To estimate available above-, belowground biomass and volume stocks for thicket and trees.

1.4 Research Questions

1) How much thicket is remaining and how much has been lost during the last two decades?
2) What are the MPEs for the selected biomass models? Are they significantly different from zero?
3) What are the MPEs for the selected volume models? Are they significantly different from zero?
4) Do volume and biomass for thicket relates with that of trees?

1.5 Conceptual and Theoretical Framework of the Study

Itigi thicket is under threat of being depleted due to anthropogenic activities which led to a loss of about 50 % of thicket area. These anthropogenic activities include; clearing land for agriculture and settlement, wildfires and cutting trees and thicket for fuel wood and charcoaling (WWF, 2014). Loss of Itigi thicket means loss of tangible and intangible benefits offered by Itigi thicket (Figure 1). Therefore, information of available biomass and volume stocks of thicket and tree species in Itigi thicket is very important for planning management of Itigi thicket.

As mentioned earlier, REDD+ offers an opportunity to support management of different vegetations including thicket. REDD+ is among the global initiatives for climate change mitigation measures. In order to engage in REDD+, a country needs to have necessary and reliable forest monitoring systems for carbon stocks and their changes.

However, information on forest carbon stocks and their changes has been hampered by unreliable statistics. Therefore, this study was carried out in order to support management of Itigi thicket through REDD+ initiatives. The focus of this study was to develop models and applying them to estimate biomass and volume of thicket and tree species. The biomass and volume stocks would be used to estimate carbon stocks for REDD+.

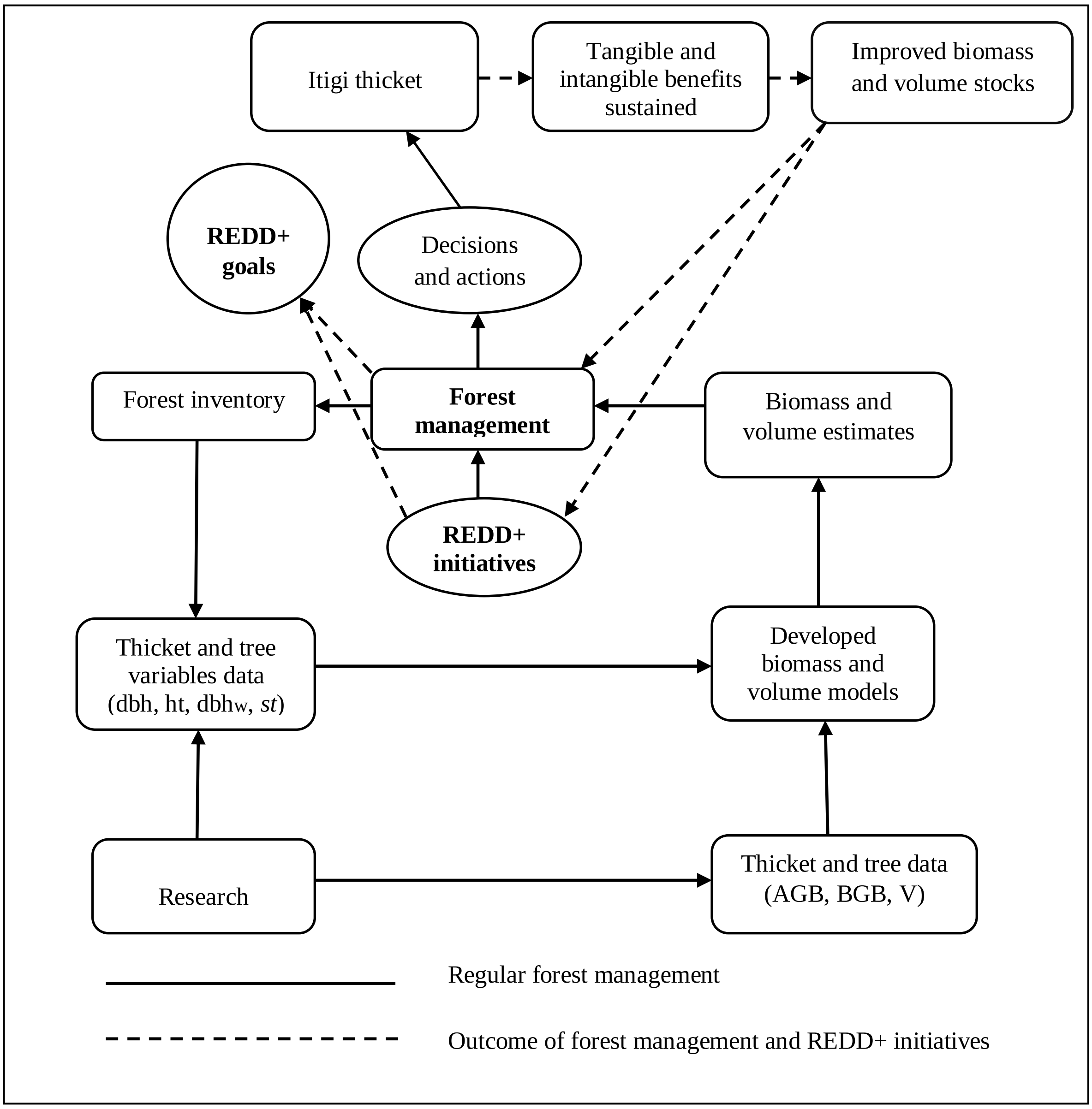

Figure 1: **Conceptual and theoretical framework of the study**

The study assumed that reliable information on biomass and volume stocks of Itigi thicket will influence decisions and actions and contribute to improved condition of Itigi thicket. In this context improved condition of thicket will serve as carbon sink, and this will be achieved through effective and informed management planning.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Overview of Itigi thicket

Woodlands in Africa are diverse vegetation formations that include woodland proper, bushland and thicket, and in some cases, wooded grassland (CIFOR, 2010). Thicket is a dense formation of evergreen deciduous shrubs and low trees (2 - 5m), often thorny and festooned with vines (Vlok *et al.,* 2003). In eastern Africa, thicket extends from central Tanzania to the lowlands of the Somalia-Masai region to Eritrea (Kindt *et al.,* 2011). Thicket is dominated by shrubs and trees that are very long-lived and are capable of sprouting after defoliation by herbivores and fire (Cowling *et al*., 2005). Thicket vegetation supports a diverse of mammals, including large and medium-sized species like African elephant (*Loxodonta africana*), black rhinoceros (*Diceros bicornis*), and African buffalo (*Syncerus caffer*) (WWF, 2014). Thicket also offers both direct tangible benefits to man (e.g. fuel wood, construction and craft materials, medicines, food) and fodder for animals. Indirect benefits including environmental services such as carbon sequestration, biodiversity and soil and water conservation (WWF, 2014).

In Tanzania, thicket extends from Manyoni District to Singida rural District and Bahi District in Dodoma region and is endemic to these areas. This vegetation is popular known as Itigi thicket, (named from Itigi town in Manyoni District, Tanzania). Itigi thicket is floristically rich and dominated by thicket species including; *P. fischeri* (Tab) Harms, *C. celastroides* Laws.

2.2 Land cover changes

Land cover describes the physical states of the land surface including cropland, forest, wetlands, pastures roads and urban areas (Di Gregorio *et al.*, 2005). Understanding the nature and extent of land cover changes as well as assessing the driving forces behind the change is essential for forecasting future patterns and in designing appropriate interventions. According to (Zhou *et al.*, 2008)land cover change often reflects the most significant impact on the environment due to human activities or natural forces and that remote sensing can be an appropriate tool for getting wide impression on land cover change. It is now widely accepted that information generated from remotely sensed data is useful for planning, and decision making.

Assessment of spatial patterns of land cover changes over a long period using images of multi-temporal coverage is now possible considering the accumulation of remotely sensed images over the past decades; as such making it possible to generate an understanding of the drivers for the changes. According to Lambin (1997), land cover change analysis is an important tool to assess global change at various spatial temporal scales.

According to Yesserie (2009), there were considerable changes of forest cover in the world during 1990 - 2010. For example in the eastern and southern Africa, deforestation rate per year was 1 841 000 ha in 1990 - 2000 and 1 839 000 ha in 2000 - 2010. The countries with the largest deforestation for 1990 - 2000 were Nigeria (-3.67 %), Indonesia (-1.75 %), Zimbabwe (-1.58 %), Myanmar (-1.17 %), Tanzania (-1.02 %), Argentina (-0.88 %), Sudan (-0.80 %), Mexico (-0.52 %), Brazil (-0.51 %) and Congo (-0.20 %). The major causes of this loss in tropical forests include agriculture settlement, fires, overgrazing, logging and fuel wood (Chakravarty *et al.*, 2014).

2.3 Allometric Models for Biomass and Volume

FAO (2004) defined biomass as organic material both AGB and BGB, and both living and dead (e.g., trees, crops, grasses, tree litter, roots). AGB consists of all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. BGB consists of all living roots excluding fine roots (less than 2 mm in diameter). In forest biomass studies, two biomass units are used, fresh weight (Araujo *et al*., 1999) and dry weight (Aboal *et al.*, 2005; Ketterings *et al*., 2001; Montagu *et al*., 2005; Saint-Andre *et al.*, 2005).

Lu (2006) mentioned three approaches to biomass assessment. These are field measurement, remote sensing and GIS-based approach. The field measurement is considered to be accurate (Lu, 2006) but proves to be very costly and time consuming (De Gier, 2003). In the case of remote sensing, ground data is needed to develop the biomass predictive model. The developed biomass model is used to estimate the tree-based biomass. While measuring the sample tree variables is easy and straightforward, measuring the sample tree biomass is difficult because the trees are large and heavy. Two methods of measuring sample tree biomass are available: (1) destructive and (2) non-destructive. The conventional destructive method is done by felling the sample tree and then weighing it. Direct weighing can only be done for small trees, but for larger trees, partitioning is necessary so that the partitions can fit into the weighing scale. In cases where the tree is large, volume of the stem is measured. Sub-samples are collected, and its fresh weight, dry weight, and volume are measured. The dry weight of the tree (biomass) is calculated based from the ratio of fresh weight (or volume) to the dry weight. This procedure requires considerable amount of labour and cost (Ketterings *et al.*, 2001; Li *et al.*, 2007) and the use of ratio is biased (Cochran, 1963). The non-destructive method does not require the trees to be felled. Measurement can be done by climbing the tree and measuring its various parts and computing the total volume. Tree density which can be found from literature is used to convert the measured volume into biomass estimate (Aboal *et al.*, 2005). Once sample tree variables and biomass data are obtained, and the biomass models is developed, it is then applied to each tree in the sample plots to obtain the plot biomass.

Like measuring biomass, measurements of volume are laborious and costly, comprising felling and complicated measurements of the trees (Snorrason and Einarsson, 2006). When felling, the trees are partitioned into small log length and their diameters and lengths are measured. Then the volumes of all logs and branches are summarized to get the volume of a tree. Once the volume of tree and tree variables data are obtained, the volume models is developed with the help of models that describe mathematically the relationship between the volumes and other more easily measured variables (Clutter *et al.*, 1983). These models are now often determined with the help of linear regression or multiple regression if there is more than one measured variable (Crow, 1988; Parresol, 1999).

According to Henry *et al.* (2011), biomass and volume models were unevenly distributed among Sub-Saharan Africa (SSA) countries. For example, most of the biomass models (70 %) were developed in Ethiopia (n = 63) and most of the volume models (44 %) were developed in Nigeria (n = 88). Most of the models found were for tropical rainforests (43 %), tropical dry forests (16 %), tropical moist forests (11 %), shrub lands (13 %) and tropical mountain forests (13 %). Most of the biomass models were developed for tropical shrub lands (23 %), tropical dry forests (23 %) and Tropical Mountain forests (21 %). On the other hand most of the volume models were developed for tropical rainforests (63 %) (Henry *et al.*, 2011).

Henry *et al.* (2011) shows that, 20 volume models for 6 tree species and general: *Brachystegia spiciformis* (2); *Cupressus lusitanica* (1); *Dalbergia melanoxylon* (2); *Julbernardia globiflora* (3); *Pinus patula* (1); *Pycnanthus angolensis* (2); Generalized (9); and seven general biomass models had been developed in Tanzania. Many studies on biomass and volume models reported in Tanzania were focused on miombo woodland (Malimbwi *et al.*, 1994; Chamshama *et al.*, 2004; Mugasha *et al.*, 2013; Mwakalukwa *et al.*, 2014; Mauya *et al.*, 2014), montane forest (Masota *et al*., 2014) and mangrove forest (Njana *et al*., 2015).

2.4 Stoking level of wood species in Tanzania

Estimation of biomass and volume are the most persistent uncertainties in understanding and monitoring the carbon cycle. This is especially true in tropical forest because of its complicated stand structure and species heterogeneity (Lu, 2006).

In Tanzania studies on biomass and volume stocks have been done in different vegetation types (Montane, sub montane forests; e.g. Munishi *et al.* (2000) and miombo woodland; e.g. Zahabu (2008)). The average AGB estimated in miombo woodland for example in Kitulangalo Forest Reserve estimated by Malimbwi *et al*. (1994) is 32.9 t per ha, Chamshama *et al*. (2004) estimated 41.04 t per ha and the average volume reported by Malimbwi *et al*. (1994) in bushland in Tabora is 17 m^3 per ha and in bushland in Iringa is 25 m^3 per ha. Also the, average volume estimate for example in miombo woodland in Tanzania estimated by NAFORMA is 55 m^3 per ha, in Kitulangalo Forest Reserve estimated by Malimbwi *et al*. (1994) is 38.7 m^3 per ha, Chamshama *et al.* (2004) estimated 76.03 m^3 per ha.

CHAPTER THREE

3.0 METHODOLOGY

3.1 Study Area

The study site is located in the northern part of Manyoni District in Singida region (5° 31' to 5°50'S and 34° 31' to 34° 49'E) (Figure 1). The altitude of study is between 1244 m and 1 300 m above mean sea level (URT, 2008). This area has three distinct seasons: a cool dry season from May to August; a hot dry season from August to November; and a rainy season from November through April. The average number of rainy days is 49 per year and the mean annual rainfall is 624 mm in the higher altitudes of Manyoni District where large area of thicket is found. The monthly temperature of the area varies from 19°C in July to 24.4°C in November.

Geologically, the area is underlained by a basement floor of granite. The soil is not stony and thereby favours the root systems of thicket species (White, 1983; Kindt *et al.*, 2011). Itigi thicket is floristically rich and dominated by thicket species including *P. fischeri* (Tab) Harms, *C. celastroides* Laws and *Dicrostachys cinerea*. (L) Wight & Arn, and the dominant tree species include *Vangueria infausta* Burch, *Vangueria madagascariensis* J. F. Gmelin, *Albizia petersiana* (Bolle) Oliv, *Canthium burtii* Bullock sensu R. B. Drumm and *Cassipourea mollis* (R.E. Fr.) Alston (URT, 2008; WWF, 2014). In addition, there are also small patches of miombo woodlands composed of miombo dominants such as *Brachystegia boehimii* Benth, *Brachystegia spiciformis* Benth, *Julbernadia globiflora* (Benth) and *Burkea africana* Hook (URT, 2008; WWF, 2014).

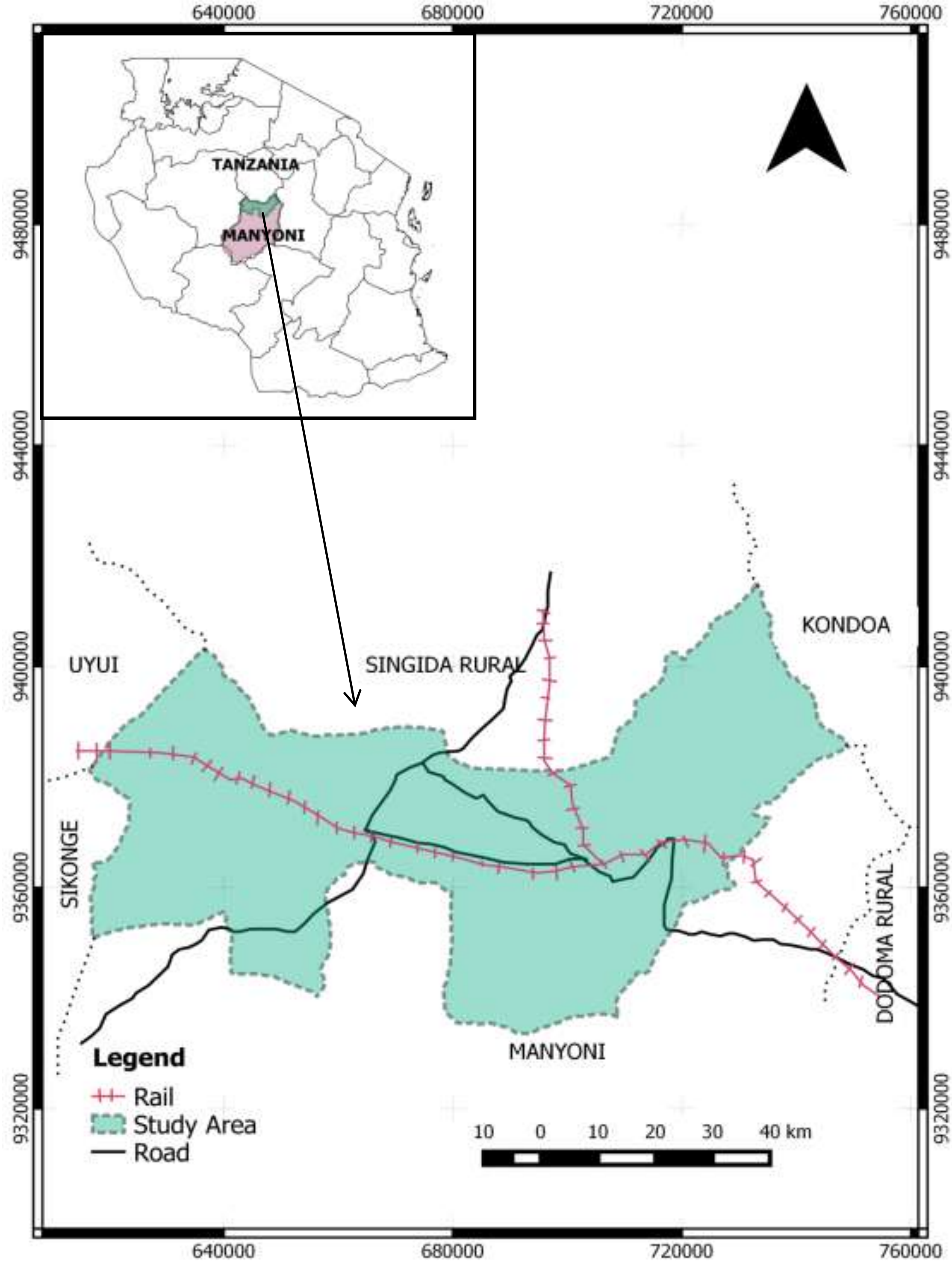

Figure 2: Location of the study area

3.2 Sampling, Data Collection and Analysis

Paper 1:

Detailed data on land cover and primary causes of land cover changes of Itigi thicket was collected at 159 plots in Itigi thicket between 2013 and 2014 (Appendix 1 and 2). Spatial data were downloaded from image suppliers. Analysis of remotely sensed data (satellite images) was based on approach described by Kashaigili *et al.* (2013) is found in *Paper 1*.

Paper 2:

From a map displaying the thicket vegetation generated in *Paper 1*, 60 coordinates of the plot centres in thicket areas were randomly selected. The coordinates of the plot centres were located in the field using a hand held GPS. The plot size was 154 m^2 (7 m radius). In thicket areas, 30 clumps of each of the two thicket species (*P. fischeri* (Tab) Harms and *C. celastroides* Laws) and 30 trees were selected for destructive sampling.

Within each plot, two clumps of each thicket species with more than 5 stems and one tree which were closest to the plot centre were selected for destructive sampling. Before felling, the thicket species was identified, the number of stems in the clump (stem count, i.e. *st*) was recorded and all stems measured for diameter at breast height (dbh) using a calliper. In addition, the total height of tallest stem (ht) in a clump was measured (Appendix 3). For each clump, a basal area weighed mean diameter at breast height of stems (dbh_w) was computed in the following way (Equation 1);

$$dbh_w = \sqrt{\frac{\sum BA_i \times 4}{st \times 3.14159}} \quad \text{...(Equation 1)}$$

where BA_i is basal area of the i^{th} stem in a clump, *st* is the stem count.

Similarly, for each selected tree, the tree species was identified and measurements of dbh and ht taken. Summary statistics for the selected thicket clumps and trees are in *Paper 2*.

The selected thicket clumps and trees were divided into above- and belowground components. The aboveground components for thicket clumps included main stems (diameter > 2 cm), branches (diameter ≤ 2 cm and ≥ 1 cm), twigs (diameter < 1 cm) and belowground components included root crown and roots. For trees the aboveground components include main stems (diameter > 5 cm), branches (diameter ≤ 5 cm and ≥ 2.5 cm), twigs (diameter < 2.5 cm) and belowground components included root crown and roots. The components were measured for their wet weight and then three sub samples were taken from each component. These sub samples were dried and the wet and dry weight of each was recorded.

The PROC NLN procedure in SAS software (SAS® Institute Inc., 2004) was used to estimate the model parameters. The selection of final models was in general based on the Akaike Information Criterion (AIC). In addition, the coefficient of determination (R^2), Root Mean Squared Error (RMSE) (Equation 2) and relative Mean Prediction Error (MPE_r) (Equation 4) for each model were reported. The reader is referred to *Paper 2* for further details about the field data collection, model selection and evaluation for biomass modelling.

Paper 3:

Similar thicket clumps and trees sampled for biomass modelling (Summary statistics for the selected thicket clumps and trees are in *Paper 3*) were used for modelling volume. The sample thicket clumps were cross cut into small stems ranging from 1 to 1.5 m in length, and each stem was measured for its mid diameter and total length excluding twigs and leaves. Similarly, trees were cross cut into small logs ranging from 2 to 2.5 m in length, and each log was measured for mid diameter and total length. The volume of individual stem/log was calculated by using Huber's formula. Total volume of thicket clumps was finally obtained by summarizing the volumes of all stems. Total volume of tree was obtained by summarizing the volumes of all small logs in a tree.

PROC NLN procedure in SAS software (SAS® Institute Inc., 2004) was also used to estimate the volume model parameters. The coefficient of determination (R^2) and Root Mean Squared Error (RMSE) (Equation 2) were reported for all models. To select the final models, the coefficient of determination (R^2) and relative Root Mean Squared Error (RMSEr) (Equation 3) were used. Details of their computations are:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(v_i - \hat{v}_i)^2}{n}} \quad \text{..........(Equation 2)}$$

$$RMSEr = \frac{RMSE}{\bar{v}_x} x100 \quad \text{..........(Equation 3)}$$

$$MPEr = \frac{MPE}{\bar{v}_x} x100 \quad \text{..........(Equation 4)}$$

Where n is the number of trees, v_i is the observed volume of tree i, $\hat{v}_i$ is the predicted volume, and $\bar{v}_x$ is the mean observed volume.

Paired *t*-tests were also done to determine whether MPEr (Equation 4) were significantly different from zero. In addition, standard deviations of residuals (STD) (Equation 5) and relative standard deviations (STDr) (Equation 6) were computed to examine the uncertainty of the models when applied over different thicket clumps or tree sizes.

$$STD = \sqrt{\sum_{i=1}^{n} \frac{(v_i - \hat{v}_i)^2}{n-1}}$$ ……………………………………………………………(Equation 5)

$$STDr = \left(\frac{STD}{\bar{v}_x}\right) x100$$ ……………………………………………………………(Equation 6)

The reader is also referred to the *Paper 3* for further details about the field data collection, model selection and evaluation.

Paper 4:

A total of 86 plots were sampled to collect data for estimation of biomass and volume of thicket and tree species. The plot size was similar with that used in *Paper 2* and *Paper 3*. Within a plot, all thicket species were identified for their names and selected for measurements (Appendix 3). For each thicket species; *st* was recorded and three stems (smallest, medium and largest) measured for dbh using a calliper. In addition, the total ht of tallest stem in a clump was measured. For each clump, dbh_w was computed using Equation 1.

Similarly, within a plot all trees were selected, identified for their names and measurements of dbh and ht taken. Table 1 shows summary statistics of sample thicket clumps and the trees measured in Itigi thicket.

Table 1: Summary statistics of sample thicket and tree species

Species	n[1]	Dbh[2] (cm)			Height (m)			Stem count		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Thicket	682	2.6	0.2	5.0	4.3	1.5	7.0	42	1	83
Tree	40	10.8	3.2	18.4	5.3	2.5	8.0			

[1]For thicket clumps, n refers clumps and for tree refers stems
[2.]For thicket clumps, dbh refers to dbh_w

In order to comply with species-specific models, thicket species were classified by their families and observed stem structures. Then, two groups were formed (group of species related to *C. celastroides* Laws and group of species related to *P. fischeri* (Tab) Harms). For each group, the respective species-specific models developed in *Paper 2* and *Paper 3* were applied to estimate biomass and volume of individual thicket clump. It was assumed that, the two thicket species (i.e. *C. celastroides* Laws and *P. fischeri* (Tab) Harms) represent average population characteristics of thicket species in Itigi thicket. In addition, student t-test was done to test if biomass and volume for thicket and tree were significantly different.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Key Findings

This section presents major findings regarding land cover dynamics for Itigi thicket, allometric models for predicting biomass and volume of thicket and tree species and stock level of biomass and volume of thicket and tree species in Itigi thicket. Detailed of major findings are in sub-section 4.1.1 to 4.1.4.

4.1.1 Analysis of land-cover changes and anthropogenic activities in Itigi thicket, Tanzania (*Paper 1*)

The results showed that thicket land cover occupies large area in the study area (Table 2). In 1991, the area occupied by thicket was 345 150.5ha (67.85 %), in 2000 was 313 451 ha (61.62 %) and in 2011 was 293 444.8 ha (57.7 %). Apparently, this large area occupied by thicket declined during 1991 - 2000 and 2000 - 2011. In 1991 - 2000, the area occupied by thicket declined by 31 699.5 ha (6.23 %) while in 2000 - 2011 the area declined by 20 006.2 ha (3.93 %).

Table 2: Cover area, change area and annual rate of change between 1991 and 2011 for Itigi thicket

Land Cover Type	Land Cover						Change Area				Annual rate of change	
	1991		2000		2011		1991 - 2000		2000 - 2011		1991 – 2000	2000 – 2011
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	(ha/yr)	(ha/yr)
Bare Land	54282.4	10.67	73034.6	14.36	91603.6	18.0	18752.2	3.64	18569	3.64	2083.6	1688.1
Thickets	345150.5	67.85	313451.0	61.62	293444.8	57.7	-31699.5	-6.23	-20006.2	-3.92	-3522.2	-1818.7
Cultivated Woodland	5654.0	1.11	10153.1	2.00	10600.2	2.1	4499.1	0.89	447.1	0.1	499.9	40.6
Grassland	103447.6	20.34	111763.2	21.97	112184.4	22.1	8315.6	1.63	421.2	0.13	924.0	38.3
Settlement	161.6	0.03	294.3	0.06	862.9	0.2	132.7	0.03	568.6	0.14	14.7	51.7
Total	**508696.0**	**100**	**508696.0**	**100**	**508696.0**	**100**						

The primary causes of land cover changes for Itigi thicket were poles as material for construction and collection of firewood (28), farming (11), charcoaling (8), fodder plants and water (19) (Table 3).

Table 3: Anthropogenic activities, their causes and the number of occurrences in Itigi thicket

SN	Anthropogenic	Main causes	Occurrence per ha
1	Woody extract	Pole as material for construction and firewood collection	28
		Logging	8
		Charcoal kiln	8
		Beekeeping-beehives making	5
2	Wood clearing	Farms	11
		Quarries (sand and stones)	3
3	Livestock grazing	Fodder/water	19
4	Fires	Hunting/Beekeeping/farms	19
5	Trespassing	Wood extract, wood clearing, and livestock grazing	28

Poles extraction and firewood collection showed sign of highest moderate and severe anthropogenic activities compared to other anthropogenic activities (Figure 2). Results of analyses show significant difference (t-test, d.f = 20, $p < 0.05$) between frequency and extent of anthropogenic activities within thicket area.

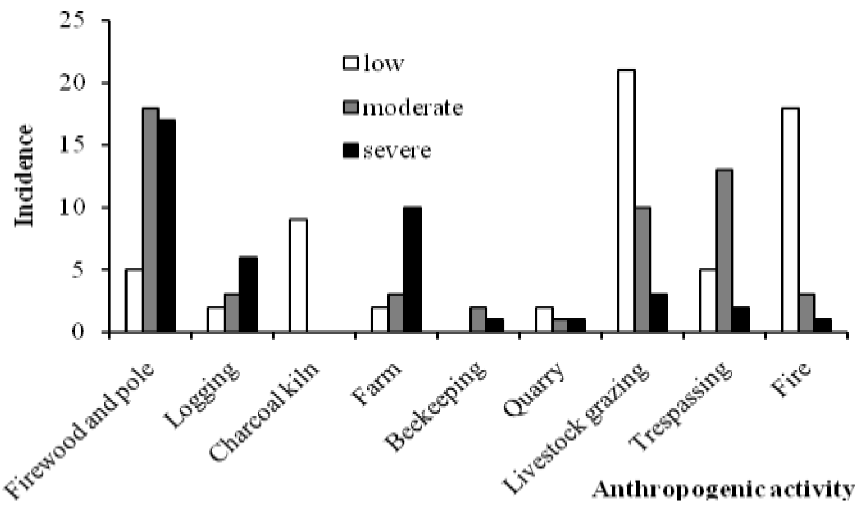

Figure 3: Extent of anthropogenic activities in Itigi thicket

4.1.2 Models predicting above- and belowground biomass of thicket and associate tree species in Itigi thicket vegetation of Tanzania (*Paper 2*)

C. celastroides Laws and *P. fischeri* (Tab) Harms are the two thicket species and *C. burtii* Bullock sensu R. B. Drumm, *C. mollis* (R.E. Fr.) Alston, *Haplocoelum foliolosum* L, *Lannea fulva* (Engl.) England and *V. madagascariensis* J. F. Gmelin are the only trees sampled for modelling. Understanding root-shoot ratios for these species is important for modelling. Because the thicket and trees are distinct, different approaches were used to quantify their roots and shoots. But similar analysis was used to determine their root-shoot ratios. The results showed that, the mean Root Square-ratios (RS) for *C. celastroides* Laws and *P. fischeri* (Tab) Harms were 0.38 and 0.51, respectively and they were significantly different (p = 0.044). The RS-ratios for both thicket species were not significantly different between dbh-classes; *C. celastroides* Laws (p = 0.430) and *P. fischeri* (Tab) Harms (p = 0.397). The mean RS-ratio for the associate trees was 0.41. For these trees, the RS-ratio was significantly different between dbh-classes ($p < 0.000$).

Parameter estimates for the selected species specific models for *C. celastroides* Laws and *P. fischeri* (Tab) Harms and mixed species models for associate trees are summarised in Table 4. For thicket and trees, despite of belowground biomass (BGB) for *C. celastroides* Laws, all models had significant parameter estimates and since they provide the lowest AIC, they were selected for further analyses by means of relative mean prediction error (MPE_r). Based on all observations, MPE_r were not significantly different from zero for any species or components. The predicted biomass when applying the aboveground biomass (AGB) and BGB models separately summarized to 45.34 kg and 52.80 kg for *C. celastroides* Laws and *P. fischeri* (Tab) Harms, respectively while for the associate trees was 60.51 kg (Table 5). The reader is referred to *Paper 2* for detailed on parameter estimates for selected and unselected models and evaluation of the selected models.

Table 4: Summary of the models and statistics for thicket clumps and associate trees

Component	Species	Model	Parameter estimates				RMSE (kg)	R^2	MPE_r (%)	AIC
			b_o	b_1	b_2	b_3				
Aboveground biomass	*Combretum celastroides* Laws	2	0.726938	2.670954	0.573718	0.203860	6.030	0.90	-0.21	196.65
	Pseudoprosopis fischeri (Tab) Harms	1	0.427622	3.405307	0.52902		6.699	0.96	1.75	202.09
	Associate tree	3	1.201291	1.507567			8.086	0.85	-0.55	212.48
Belowground biomass	*Combretum celastroides* Laws	1	0.106055	4.006166	0.349925		3.526	0.82	-0.16	163.59
	Pseudoprosopis fischeri (Tab) Harms	1	0.144225	4.153442	0.411693		3.853	0.95	1.06	168.90
	Associate trees	3	1.380314	1.167124			4.732	0.69	0.22	180.33

*Parameter estimate not significant ($p > 0.05$), selected models in bold

Table 5: Prediction accuracies observed in evaluation of the selected models for thicket and associate trees

Species	Component	Model	dbh-class (cm)	n	Biomass (kg)		MPE_r (%)	P-value
					Observed	Predicted		
Aboveground biomass	*Combretum celastroides* Laws	2	All	30	34.06	34.13	-0.21	0.9428
	Pseudoprosopis fischeri (Tab) Harms	1	All	30	36.89	36.25	1.75	0.5864
	Associate tree	3	All	30	39.81	40.00	-0.55	0.8812
Belowground biomass	*Combretum celastroides* Laws	1	All	30	11.20	11.21	-0.16	0.9748
	Pseudoprosopis fischeri (Tab) Harms	1	All	30	16.73	16.55	1.06	0.7953
	Associate trees	3	All	30	20.55	20.51	0.22	0.9577

4.1.3 Models for prediction of volume of thicket and associate tree species in Itigi thicket vegetation of Tanzania (*Paper 3*)

Similarly, the *C. celastroide* Laws and *P. fischeri* (Tab) Harms (thicket species) and *C. burtii* Bullock sensu R. B. Drumm, *C. mollis* (R.E. Fr.) Alston, *H. foliolosum* L, *L. fulva* (Engl.) England and *V. madagascariensis* Burch (Associate trees) were sampled for modelling volume. Parameter estimates and performance criteria for thicket and trees models are summarized in Table 6. For thicket species R^2 varied from 0.64 to 0.93. Based on the model selection criteria, model 2 was judged best by both R^2 and RMSEr for both thicket species. For associate trees, model 4 was also judged best by R^2 and RMSEr. For all species, none of the selected models had MPE values statistically significant different from zero ($p > 0.05$).

The selected models for thicket clumps and associate trees were further evaluated by means of relative MPEr (%) (Table 7). Overall, for all observations, no MPEr (%) were significantly different from zero for any species. However, for *C. Celastroides* Laws, the models significantly over-predicted the volume for clumps in the medium dbh-class. For *P. fischeri* (Tab) Harms, no MPE (%) different from zero were seen in dbh classes. Similarly, no MPE (%) different from zero were seen in dbh-classes for trees. The reader is referred to *Paper 3* for detailed on parameter estimates for selected and unselected models and evaluation of the selected models.

Table 6: Summary of the models and statistics for thicket clumps and associate trees

Species	**n**	**Mean observed volume (m^3)**	**Model**	**β_0**	**β_1**	**β_2**	**β_3**	**R^2**	**RMSEr %**	**MPEr %**
Combretum celastroides Laws	30	0.0291	2	0.000230	2.461515	0.908853	0.453408	0.69	31.8	1.20
Pseudoprosopis fischeri (Tab) Harms	30	0.0256	2	0.000166	2.217730	0.546812	0.790309	0.93	23.3	0.50
Associate trees	30	0.0445	4	0.000420	1.50092	0.64185		0.93	14.3	-0.13

*Parameter estimate not significant ($p > 0.05$), selected models in bold

Table 7: Prediction accuracies observed in evaluation of the selected models for thicket and associate trees

Species	**Dbh- class[1]**	**n**	**Model**	**Total volume (m^3)**		**MPEr %**	**p-Value for MPE**	**STD m^3**	**STDr %**
				Observed	**Predicted**				
Combretum celastroides Laws	All	30	2	0.0291	0.0209	1.2	0.8440	0.0094	32.3
Pseudoprosopis fischeri (Tab) Harms	All	30	2	0.0256	0.0255	0.5	0.9155	0.0061	23.3
Associate trees	All	30	4	0.0445	0.0446	-0.13	0.9600	0.0065	14.5

[1] For thicket clumps, dbh class refers to dbh_w

The findings regarding the differences when using dbh_w from all stems and dbh_w from the three stems as an input variable for the models are presented in Table 8. Overall, for all observations, there were no significantly different from zero for any species ($p > 0.01$).

Table 8: Statistical summary for dbh_w from all stems and three stems

Species	dbh_w	Mean	Max	Min	STD	*p*-Value
Combretum celastroides Laws	All stems	2.4	3.2	1.5	0.3	0.015
	Three stems	2.8	3.8	1.6		
Pseudoprosopsis fischeri (Tab) Harms	All stems	2.2	3.0	1.2	0.2	0.339
	Three stems	2.3	3.8	1.3		

4.1.4 Estimation of volume and biomass of thicket and tree species in Itigi thicket, Tanzania (*Paper 4*)

The total number of thicket and tree species observed in Itigi thicket is 28 including 13 of thicket species and 15 of tree species. Figure 3 shows the wood species which contribute high in term abundance, volume and biomass. The wood species include; *P. fischeri* (Tab) Harms (Tab) Harms, *C. celastroides* Laws, *D. cinerea*. (L) and *Baphia massaiensis* Taub. These wood species with exception of *D. cinerea*. (L) and *B. massaiensis* Taub are endemic to Itigi thicket.

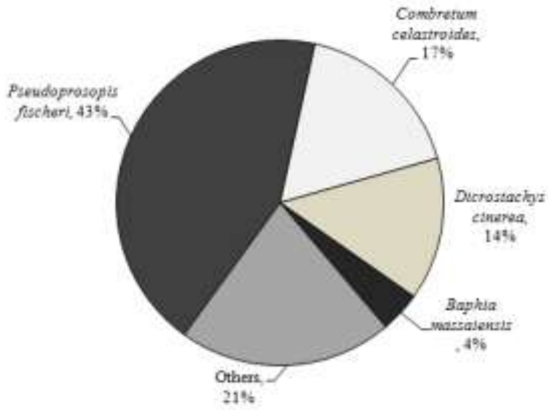

Figure 4: Major wood species in Itigi thicket

Table 9 show the statistics of stand parameters for Itigi thicket. The results show that, the volume estimates per ha of Itigi thicket is 8.1±1.0 m^3. When using t test, comparisons of volume with thicket and tree species showed that the volume were statistically significant different (p = 0.000). The AGB estimates per ha of Itigi thicket is 8.7±1.2 t and BGB estimates per ha is 4.1±0.6 t (Table 9). Biomass for thicket and tree species were statistically significant different (p = 0.000). The results also show that, basal area of Itigi thicket is 2.2 m^2 per ha.

Table 9: Statistics of stand parameters for Itigi thicket

Statistical parameters	Form	Stems per ha	Basal area (G, m^2/ha)	Aboveground biomass (AGB, t/ha)	Belowground biomass (BGB, t/ha)	Volume (V, m^3/ha)
Mean	Thicket	5735	2.0	7.8	3.6	7.2
	Tree	30	0.2	0.9	0.5	0.9
	all	5765	2.2	8.7	4.0	8.1
Standard Error	all	646	0.3	1.2	0.6	1.0
Standard Deviation	all	5992	2.5	10.7	5.3	9.1
Number of plots		86	86	86	86	86

The distribution of number of stems, volume and biomass by diameter classes and species is shown in detailed in *Paper 4*.

4.2 Discussions

The average overall accuracy of over 80% indicates the reliability of the classifications (Yesserie, 2009) thus giving confidence on the detected changes (Coppin *et al.*, 2004; Chakravarty *et al.*, 2014) using a post-classification change detection of classified images (pixel-by-pixel comparison). The change analysis has revealed that thicket cover declined from 345 150.5 ha in 1991 to 313 451 ha in 2000 and 293 444.3 ha in 2011. This reduction was also demonstrated by the increase of bare land from 54 282.4 ha in 1991 to 73 034.6 ha in 2000 and 91 603.6 ha in 2011, cultivated woodland from 5 654 ha in 1991 to 10 153 ha 2000 and 10 600.2 ha in 2011 and settlement from161.6 ha in 1991 to 294.3 ha in 2000 and 862.9 ha in 2011. Furthermore, thicket covers loss was also reflected in the mapped thicket area. These results are in agreement with WWF (2014) and Almond (2000) in WWF (2014) reports which showed the loss of Itigi thicket cover between 1990 and 2000. The annual rate of change for thicket land cover between 1991 and 2000 was higher compared to that of 2000 to 2011. This estimate is in line with that reported by FAO FRA 2001 and 2010 which indicate considerable deforestation in the world during 1990 - 2010 (Yesserie, 2009). The major causes of this loss include agriculture settlement, fires, overgrazing, logging and fuel wood (Chakravarty *et al.*, 2014).

Similarly, this study showed multi anthropogenic activities in Itigi thicket which associated with conversion of thicket to non-thicket areas. The major anthropogenic activities reported in this study include wood extract being caused by extraction of pole for construction and firewood collection, livestock grazing, charcoal burning and fires. Comparable results was reported by Mligo (2012), that fires, cutting trees for fuel wood and poles, overgrazing and charcoaling are the major anthropogenic activities in Makurunge woodland. Cochrane *et al.* (1999) showed that the forest ecosystem is increasingly threatened by anthropogenic activities such as agriculture and settlements, selective logging and fires.

Results of Itigi land cover showed gradual change of thicket cover. It is therefore important to understand why thicket cover is declining. This understanding could go a long way in design of interventions for promotion of sustainable management. Furthermore, the need for accurate and reliable information about thicket cover change to inform debates, discussions and decision making on thicket management and conservation in Tanzania still exists (URT, 2008).

This study provided the models which are very important tools for assessing biomass and volume of thicket and tree species in Itigi thicket. The models presented in this study are the first ones developed for thicket in Tanzania. Two thicket species and five tree species were focused, mainly because of limited resources to cover the entire thicket and tree species present in Itigi thicket. The selection of data for modelling was based on randomly distributed sample plots within the study site to ensure that the samples to be as representative as possible. Thus, samples with wide range in sizes were covered, i.e. for thicket dbh_w ranged from 1.2 cm to 3.2 cm, ht from 3 m to 6.5 m and *st* from 6 to 57 and for trees dbh ranged from 6.1 cm to 18 cm (*Paper 2 and Paper 3*). Use of modelling data with appropriate numbers of both small and large clumps is important in order to avoid extrapolation, and the uncertainty related to this, as much as possible.

The number of sample for this study was relatively small (i.e. 60 for thicket and 30 for trees) compared to for example recently developed biomass models for miombo woodlands and mangrove forest in Tanzania (Mugasha *et al.*, 2013; Mwakalukwa *et al.*, 2014; Njana *et al.*, 2015). However, a large number of previously developed models in sub-Saharan Africa have also used fewer observations than in the present study (Henry *et al.*, 2011).

Generally for thicket clumps, large parts of the variations in biomass were explained by dbh_w and *st*. While for trees, large parts of the variations were explained by dbh. Inclusion of ht as an independent variable for both thicket and trees explained variations only marginally. It was also noted that, for thicket, large parts of the variations in volume were explained by dbh_w, *st* and ht. While for trees, large parts of the variations were explained by dbh and ht. Inclusion of ht as an independent variable in volume modelling for both thicket and trees improved the performance criteria R^2 and RMSEr. The improvements were moderate, however, which also conform with several previous studies (Malimbwi *et al.*, 1994; Abbot *et al.*, 1997; Guendehou *et al.*, 2012).

The presented models are meant to be applied, based on forest inventories, for estimating biomass or volume per unit area or in total for a certain forest area. The most accurate biomass and volume estimate will of course be achieved by measuring dbh of all stems in the clumps. However, since measuring dbh of all stems is time consuming, an alternative could be to measure dbh for example the smallest, a medium and the largest stem regarding dbh in a clump, and then apply the dbh_w of these three stems as input for the models. Such a procedure will of course increase the uncertainty in the biomass and volume estimates when applying the models (Table 8), but it will also reduce time consumption in practical inventories considerably.

The species-specific thicket clump models developed may generally be applied inside the study site (Manyoni). The models may also be applied outside this site where Itigi thicket extends (i.e. Singida rural District and Bahi District in Dodoma region) because growing condition here are very similar. Although Itigi thicket comprise of more than 10 different species, a recent sample plot inventory in the area showed that the two selected species contribute to more than 50 % of the total stem density (*Paper 4*). For practical reasons when estimating biomass or volume for larger areas, it is recommend the models to be applied also to remaining thickets species with similar morphology. The uncertainty in biomass or volume estimates will of course increase by doing this, but this is the only option since models do not exist for the remaining species. The application recommendation for tree models is similar to those of the thicket clumps; for the study site, and outside where the Itigi thicket vegetation extends.

This study reported a total of 28 thicket and tree species. According to Fanshawe (1971) and Almond (2000) in WWF (2014), there were 100 wood species in Itigi thicket characterized by *Baphia burttii, B. massaiensis* Taub, *Bussea massaiensis, Burttia prunoides, C. celastroides* Laws, *Grewia burttii, P. fischeri* (Tab) Harms, and *Tapiphyllum floribundum* (White 1983). Thus the number of wood species reported in this study is relatively lower compared to that reported in the same area by WWF (2014). This was most likely because the WWF (2014) aimed to capture all plant species available ecologically irrespective of abundance while this study is more likely to catch the big contributors for volume and biomass.

Based on the results, thicket species were most wood species contributor in term of abundance, volume and biomass in Itigi thicket. This was revealed by four thicket species (*P. fischeri* (Tab) Harms, *C. celastroides* Laws and *D. cinerea*.(L) Wight and Arn and *B. massaiensis* (Taub) found to contribute high in the area (Figure 3). Moreover, this study observed few number of tree species with diameter between 0 - 5.0 and > 10.0 cm (*Paper 4*). It is very possible that the biomass and volume of thicket and tree species in Itigi thicket would be higher if this vegetation had not been subjected to anthropogenic disturbances. It was argued by Brown (1997) that forests that have been subjected to anthropogenic disturbances tend to have lower wood stocks than their potential.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study has revealed land cover changes in the Itigi thicket between 1991 and 2000 and between 2000 and 2011. The findings showed a decrease of thicket and increase of non-thicket area such as bareland, grassland, settlement and cultivated woodland due to anthropogenic activities including wood extract for fuel wood and construction, wood clearing for agriculture, livestock grazing, fires and trespassing.

The model fitting showed that large parts of the variation in biomass of thicket were explained by basal area weighed mean diameter at breast height and number of stems in the clumps and in volume were explained by basal area weighed mean diameter at breast height, height and number of stems. For trees most variation in biomass was explained by diameter at breast height only and in volume was explained by diameter at breast height and height. Although there will be some uncertainties related to biomass and volume estimates for large areas, for practical reasons, it is recommended the selected models to be applied to the entire area where Itigi thicket extends outside our study site, and also to those thicket and associate tree species present that were not included in the data used for modelling.

The results showed that, Itigi thicket is characterised by few number of wood species. Despite the scarcity of large diameter trees, the vegetation has larger number of stems per ha and reasonable amount of biomass and volume per ha.

The methods used in this study to assess land cover changes and estimates of biomass and volume of wood species highlight the importance of integrating remote sensing and forest inventory in understanding the thicket resources dynamics and generating information that could be used to overcome the Itigi thicket problems for the sustainability of this unique vegetation.

5.2 Recommendations

Based on what has been accomplished by this study the following areas for further research were identified.

(i) Since thicket and trees are quite diverse in Itigi thicket, there is a need to develop biomass and volume models for other thicket and tree species not covered in this study.

(ii) Based in this study, determination of diameter of clump of thicket species was challenging. It is therefore important that height prediction models are developed for thicket species in Itigi thicket.

(iii) Basic density is important not only for biomass determination but also useful for other issues such as industrial utilization. Determination of basic density of thicket such as *C. celastroides* Laws not covered in this study is therefore important.

(iv) Growth studies for thicket and trees are lacking. It is therefore high time such studies are conducted.

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APPENDICES

Appendix 1: Remote sensing ground truthing form

Date---
Stratum #---
Season--
Time: from--------------------------------------- to ---

Plot #	Plot location		Altitude	Cover	Area name	Remarks
	Y	X				

Appendix 2: Anthropogenic activities field form

Date---
Stratum #---
Coordinate------------------------------------ elevation---------------------------------

Plot #	Anthropogenic activity	Primary causes of anthropogenic activity	Evidence of activity	Rate of anthropogenic activity			
				absent (0)	low (1)	moderate (2)	Severe (3)

Appendix 3: Destructive and non-destructive field form

Date--

Stratum number---

Plot #--

Plot location (Y)----------------- (X) ----------------- UTM----------------------------

(i) Thicket

Clump #	Species code	Species name		Dbh (mm)			Total ht (m)	Stem count	Sample #
		Local	Botanical	Small	Medium	Large			

(ii) Associate trees

Tree #	Species code	Species name		dbh (cm)	Total ht (cm)	Sample #
		Local	Botanical			

CHAPTER SIX

PAPER ONE

Analysis of land-cover changes and anthropogenic activities in Itigi Thicket, Tanzania

Joseph S. Makero[a] and Japhet J. Kashaigili[b]

[a] Forestry Training Institute, Olmotonyi, P. O. Box 943, Arusha, Tanzania
[b] Department of Forest Resources Assessment and Management, Sokoine University of Agriculture, P.O. Box 3013, Morogoro, Tanzania

*Corresponding author: Tel +0255 752 356 999/655 408 403

Email: makerojons@yahoo.com

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Analysis of Land-Cover Changes and Anthropogenic Activities in Itigi Thicket, Tanzania

Joseph S. Makero[1], **Japhet J. Kashaigili**[2*]

[1]Forestry Training Institute, Arusha, Tanzania
[2]Department of Forest Resources Assessment and Management, Sokoine University of Agriculture, Morogoro, Tanzania
Email: *jkashaigili@gmail.com

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Abstract

Assessing land cover changes from the 1991 to 2011 for Itigi thicket is imperative for determining changes between land cover types and understanding anthropogenic impact during this period. Remote sensing (RS) data, Geographic Information System (GIS) techniques and forest inventory data were used. ILWIS 3.3 Academic software was used to analyze the satellite imageries to determine the land use, land cover change; while data on anthropogenic activities were analysed in MS Excel software. The results showed that between 1991/2000 and 2000/2011, the areas of thicket declined by 6.23% while non-thicket areas increased by 3.92%. The decline in thicket areas was attributed to increase in anthropogenic activities such as wood extraction, clearing for agriculture, livestock grazing and fires. The study highlights the importance of integrating remote sensing and forest inventory in understanding the thicket resources dynamics and generating information that could be used to overcome the Itigi thicket problems for the sustainability of this unique vegetation.

Keywords

Itigi Thicket, Land Cover Change, Remote Sensing, GIS

1. Introduction

Thicket is a dense formation of evergreen and weakly deciduous shrubs and low trees (2 - 5 m), often spiny and festooned with vines [1]. According to [2], thicket is generally influenced by soil type and structure, and is mainly found in Africa (e.g. Madagascar, Tanzania, Zambia), west Asia (e.g. Sound Arabia, India), eastern and northern Australia and America (e.g. Mexico, central America, north western Argentina, central Bolivia, north eastern Argentina, Paraguay, eastern Brazil). In East Africa, thickets rise from central Tanzania to the lowlands of the Somalia-Masai region to Eritrea [3] [4]. The climate of thicket's core area is semi-arid to sub-humid (250 - 800 $mm \cdot yr^{-1}$) and subtropical to warm-temperate (largely frost-free). Thicket has a rich flora estimated to 1600 species, 20% of which are endemic to the Subtropical areas [4]. Thicket is dominated by trees and shrubs that are very long-lived and are capable of sprouting after defoliation from herbivores, frost and fire [4].

In Tanzania, thicket falls in the semi-arid areas of central parts of the country. This thicket is endemic to Itigi in Manyoni District and thus named Itigi thicket. Itigi thicket constitutes one fifth of the total area of Manyoni District and it represents a globally unique biodiversity resource both for national and international importance. The vast and relatively dense vegetation are also reported to be among the last strongholds for large mammals species such as African elephant (*Loxodonta africana*), black rhinoceros (*Diceros bicornis*) and African buffalo (Syncer us caffer) [5].

Although Itigi thicket vegetation is essential for the survival of humankind and wild animals, it has been threatened by an array of anthropogenic activities, because of its complex and fragile ecosystems. [6] [7] pointed out that, anthropogenic activities have transformed the earth's surface by converting natural forests, savannas and steppes into agricultural lands and substantially modifying others with significant consequences for land cover, biodiversity, soil condition, water and sediment flows. Land cover changes have accelerated in the 20th Century, both in pace and intensity, because of increased intensity of anthropogenic activities [8]. According to [9], land cover describes the physical states of the land surface including cropland, forest, wetlands, pastures roads and urban areas. Understanding the nature and extent of land cover changes as well as assessing the driving forces behind the change is essential for explaining the past and forecasting future patterns and in designing appropriate interventions.

The mid-resolution, multi-temporal satellite images such as Landsat, has been the most reliable source of data for monitoring forest change. These images provide encoded radiance data in the visible near-and middle-infrared spectra, in which most mature tropical forest can be spectrally distinguished from farm, fallow land and other non-forest vegetation [10] [11] [12] [13].

According to [14], land cover change analysis is an important tool to assess global change at various spatial temporal scales. [15] affirmed that it reflects the dimension of human activities on a given environment. According to [16] land cover change often reflects the most significant impact on the environment due to human activities or natural forces and that remote sensing can be an appropriate tool for getting wide impression on land cover change. It is now widely accepted that information generated from remotely sensed data is useful for planning, and decision making. For example, according to [17], for the resource manager, a particular attraction of satellite remote sensing technology is the ability to provide consistent measurements of landscape condition, allowing detection of both abrupt changes and slow trends over time. Detection and characterization of change in key resource attributes allows resource managers to monitor landscape dynamics over large areas, and with less costs [18]. Furthermore, long-term change detection results can provide insight into the stressors and drivers of change, potentially allowing for management strategies targeted toward cause rather than simply the symptoms of the cause [17]. The assessment of spatial patterns of land cover changes over a long period using images of multi-temporal coverage is now possible considering the accumulation of remotely sensed images over the past decades; as such making it possible to generate an understanding of the drivers for the changes.

Like other forest types, Itigi thicket has been affected by shifting cultivation, pasture, charcoaling and mining [5]. Since, it is adjacent to the rural population who depends directly on the land for their livelihoods. This rural population is causing resource degradation brought about by the decrease in the area under thicket vegetation and its conversion into other types of land use and land cover that are human-managed systems. Previous studies for example [19] reported on biodiversity features of Itigi thicket and the [5] reported on the monitoring of the Itigi thicket using Landsat. Since no study reported on anthropogenic activities and land cover changes in Itigi thicket, it was worthy to detailed assessment of anthropogenic activities and land cover changes in Itigi thicket.

Therefore this paper presents an assessment of land cover changes of Itigi thicket in Tanzania using Landsat data sets acquired in 1991, 2000 and 2011 to address three questions: 1) How much thicket is remaining and how much has been lost during the last two decades? 2) What is the rate of change of Itigi thicket? 3) What are the major causes of land cover changes? The information generated from this study is central for planning sustainable development and management of Itigi thicket.

2. Materials and Methods

2.1. Site Description

Data for this study were collected in Itigi thicket located in the northern part of Manyoni district, Singida Region (5˚31' - 5˚50'S and 34˚31' - 34˚49'E) (**Figure 1**). The altitude of the study area ranges between 1244 and 1300 m.a.s.l [20]. The area has unimodal rainfall with annual mean rainfall of 624 mm. The minimum temperature is in July (19˚C) while the maximum temperature is in November (24.4˚C). The area has granite soil which is not stony and therefore favours the root systems of thicket species to easily penetrate [3] [21].

Itigi thicket is floristically rich and dominated by *Pseudo prosopsis fischeri* (Taub.) Harms and *Combretum celastroides* Laws. Other thicket species includes: *Craibia abbreviata* subsp. burtii, *Combretum paniculatum* Vent., *Dichrostachys cinerea* (L.) Wight & Arn, *Croton scheffleri* Pax, *Excoecaria bussei* (Pax) Pax, *Grewia forbesii* Harv. ex Mast, *Grewia similis* K. Schum, *Ochna ovate* F. Hoffm, *Rinorea angustifolia* Grey-Wilson, *Tennantia sennii* (Chiov.) Verdc. & Bridson, and *Zanthoxylum chalebium* Engl. Within Itigi thicket there are also low trees (associate trees) such as *Acacia tortilis* (Forsk.) Hayne, Arzeyk., *Baphia massaiensis* Taub., *Cassipourea mollis* (R. E. Fr.) Alston, *Haplocoelum foliolosum*, *Lannea fulva* (Engl.) Engl, *Senna singueana* (Delile) Lock, *Maerua triphylla* A. Rich., *Vangueriama dagascariens* is J. F. Gmelin. In addition, there are small patches of miombo woodland composed of miombo dominants such as *Brachystegia*

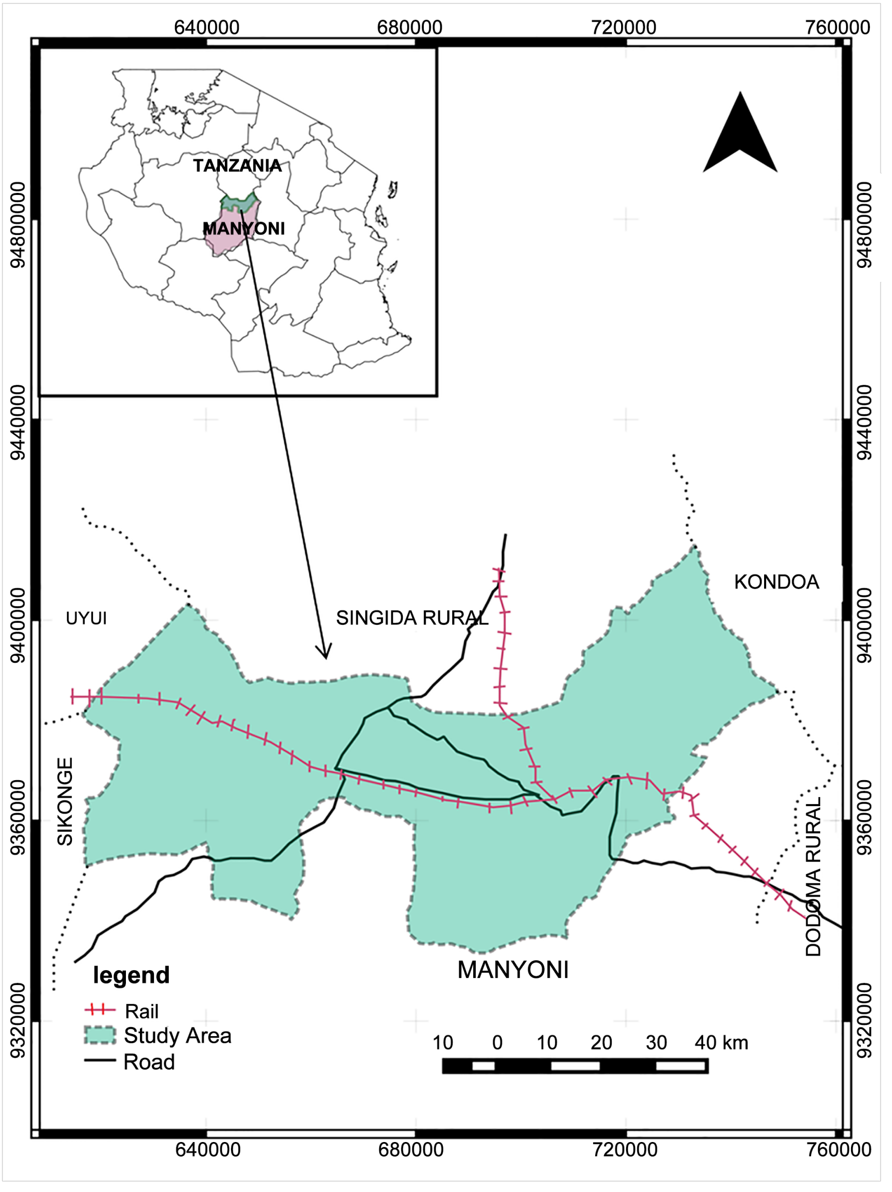


Figure 1. Location of the study area.

boehimii Benth., *Brachystegia spiciformis* Benth., *Julbernadia globiflora* (Benth.) and *Burkea africana* [5] [22].

2.2. Methods

Data of this study were collected by using RS and GIS techniques. In addition, field survey and key informant interviews were used to get information of the causes of land cover changes at the present and past years.

2.2.1. Imageries Data Collection and Analysis

Image selection and acquisition: In consideration of cloud cover, the seasonality and phonological effects [23], image listed in Table 1 were selected for image processing

Table 1. Landsat images used in the analysis of thicket cover changes.

Image	Path/row	Acquisition date	Season
Landsat TM	169/64	August 1991	Dry
Landsat ETM+	169/64	September 2000	Dry
Landsat TM	169/64	July 2011	Dry

and change analysis. The image selected was from dry season in order to acquire images with minimum cloud cover and also to avoid differences due to season effects. In this study land sat images of 1991, 2000 and 2011 were used for land use land cover change classifications.

Image processing: Image processing involved three stages, these were: Image preprocessing, rectification or georeferencing and image enhancement. 1) Image preprocessing, the methods for image analysis required the use of both visual and digital image processing. Both visual and digital image processing was done. Prior to image processing images were extracted from the full scenes using ILWIS 3.3 Academic software to subset scenes into area of interest (AOI) followed by rectification. 2) Image rectification, Image rectification were performed in order to correct data for distortion or degradation which may result from the image acquisition process. To ensure accurate identification of temporal changes and geometric compatibility with other sources of information, the images were geo-coorded to the coordinate and mapping system of the national topographic maps, *i.e.* UTM coordinate zone 36 south, Spheroid clarke 1880, Datum Arc 1960, based on a previous georeferenced Landsat TM images of July 2011. Since the images had already been corrected for radiometric distortions and available as geo-cover datasets with no apparent noise, the created sub-scene were only subjected to geometric correction. 3) Image enhancement, In order to reinforce the visual interpretability of images, a colour composite (Landsat TM bands 4, 5, and 3) was prepared and its contrast was stretched using a Gaussian distribution, a 3 × 3 high pass filter was applied to the colour composite to further enhance visual interpretability of linear features e.g. Rivers, and land use features like agricultural land, forests etc. All image processing were carried out using ILWIS 3.3 Academic software.

Preliminary Image classification and ground truthing: Preliminary Image classification: Within the scope of this study, image classification is defined as the extraction of differentiated land use and land cover categories from remote sensing data. Supervised image classification using Maximum Likelihood Classifier (MLC) was used to create base map which was then used for ground truthing. The maximum likelihood classifier was selected since unlike other classifiers it considers the spectral variation within each category and the overlap covering the different classes [23]. Before going to field, to implement ground truthing, preliminary image classification was performed to roughly identify vegetation types and other land use and land cover classes. Sets of hardcopy of colour composite images with overlays of roads and UTM coordinates were produced using image acquired on July 2011 and used as a base-map during the ground truthing.

Ground truthing was done in order to verify and modify land use land covers obtained during preliminary image interpretation. A hand-held GPS GPS was used to locate sampled land cover observations. During the ground truthing, the following major land cover classes were identified: thickets, grassland, bareland, settlement and cultivated woodland.

Final image classification: Supervised image classification using maximum likelihood classifier (MLC) was utilized in this study. The advantage of digital image classification is that it can provide efficient, consistent and repeatable routines for mapping large areas [23]. Supervised classification process involved selection of training sites on the image. Training sites are sites of pixels that represent specific land classes to be mapped [24]. They are pixels that represent what is recognized as discernible pattern or potential cover classes. Training sites were generated by on-screen digitizing of selected areas for each land cover class identified on the colour composite. Training was iterative process, whereby the selected pixels were evaluated by performing an estimated classification. Based on the inspection, training samples were refined until a satisfactory result was obtained. The objective was to produce thematic classes that resemble or can be related to the actual land cover types on the earth's surface.

Classification of Accuracy Assessment: Land cover maps derived from classification of images usually contain some sort of errors due to several factors that range from classification techniques to methods of satellite data capture. Hence, evaluation of classification results is an important process in the classification procedure [25]. Among the common measures used for measuring the accuracy of thematic maps derived from multispectral imagery, error/confusion matrix was used. An error matrix is a square assortment of numbers defined in rows and columns that represent the number of sample units assigned to a particular category relative to the actual category as confirmed on the ground.

Preparation of land use land cover maps: Classified images were recorded to respective classes (*i.e.*: thickets, grassland, bareland, settlement and cultivated woodland). Following the recoding, images were filtered using a 3 × 3 majority-neighbourhood filter. The classified images were filtered in order to eliminate patches smaller than a specified value and replace them with the value that is most common among the neighbouring pixels. A mosaic operation was not performed because images acquired cover the entire study area.

Land use land covers change detection analysis: Change detection is a very common and powerful application of satellite based remote sensing. Change detection entails findings the type, amount and location of land use changes that are taking place [23].

In this study, post classification comparison was used to quantify the extent of land cover changes over the 20 years period (1991, 2000, and 2011). The advantage of post classification comparison is that it bypasses the difficulties associated with the analysis of the images that are acquired at different times of the year, or by different sensors and results in high change detection accuracy [26].

Assessment of the rate of cover change: Estimation for the rate of change for different land covers was computed based on the following formulae [27].

$$\%\ \text{Change}_{year\ x} = \frac{Area_{i\ year\ x} - Area_{i\ year\ x+1}}{\sum_{i=1}^{n} Area_{i\ year\ x}} \times 100 \quad (1)$$

$$\text{Annual rate of change} = \frac{Area_{i\ year\ x} - Area_{i\ year\ x+1}}{t_{years}} \quad (2)$$

$$\%\text{Annual rate of change} = \frac{Area_{i\ year\ x} - Area_{i\ year\ x+1}}{\sum_{i=1}^{n} Area_{i\ year\ x}\, x\, t_{years}} \times 100 \quad (3)$$

where, $Area_i$ year x is area of cover i at the first date, $Area_i$ year $x + 1$ is area of cover i at the second, $\sum_{i=1}^{n} Area_{i\ year\ x}$ is the total cover area at the first date and t_{years} is period in years between the first and second scene acquisition dates.

2.2.2. Anthropogenic Activities Data Collection and Analysis

The field survey was carried out in two stages: 1) reconnaissance survey to acquaint with study area, delineate thicket boundaries and stratify thicket area using RS techniques, 2) detailed field survey for assessment of anthropogenic activities using visual observation. At random, 86 plots with an area of 0.0154 ha were established and their coordinates were taken using a hand held Global positioning system (GPS). In each plot assessment of anthropogenic activities was done (**Table 2**).

Both descriptive and inferential statistical methods were used to analyze the quantitative data. Descriptive statistics such as frequency and percentages were used to explain and illustrate primary causes of anthropogenic activities in Itigi thicket. Inferential data analysis was done to determine the extent of anthropogenic activities per ha and to test the significance between frequency and extent of anthropogenic activities within thicket area. The Microsoft Excel software package was used for the qualitative and quantitative data analysis. The frequency and extent per ha were computed in the following ways;

$$f_{ha} = \frac{f}{p \times n} \quad (4)$$

whereby f_{ha} is frequency per ha of individual anthropogenic activity (count/ha), f is frequency (count), p is plot size and n is number of plots inventoried.

$$E_{ha} = \frac{Ab}{p \times n} \quad (5)$$

whereby E_{ha} is extent per ha of individual anthropogenic activity (abundance per ha), Ab is abundance of anthropogenic activity (number of count in a plot), p is plot size and n is number of plots inventoried.

$$RAb = \frac{ni}{N} \times 100 \quad (6)$$

whereby RAb is relative abundance of individual anthropogenic activity, Ab is abundance of anthropogenic activity (number of count in a plot), N is total number of individual anthropogenic activities recorded in an area.

Table 2. Categories of anthropogenic activities variables recorded in the Itigi thicket.

SN	Anthropogenic activity	Primary causes of anthropogenic activity	Indicator	Extent of anthropogenic activity			
				absent (0)	low (1)	moderate (2)	severe (3)
1	Woody extraction	Pole for house construction and firewood	stump < 15 cm	None	1 - 20	21 - 50	>50
		Timber	stump > 15 cm	None	1 - 10	11 - 25	>25
		Cultivation	farm/cleared area	None	occasional	frequent	heavily
		Mining	cleared area that excavated	None	occasional	frequent	heavily
		Charcoal	charcoal kiln	None	1 - 2	3 - 6	>6
			stumps close to charcoal kiln	None	1 - 20	21 - 50	>50
2	Woody thinning and pruning	Beekeeping	beehive/ pruned woody species/traces	None	occasional	frequent	heavily
3	Livestock grazing	Pasture/water	livestock faeces	None	occasional	frequent	heavily
			browsing traces	None	occasional	frequent	heavily
4	Fires	Hunting/ Beekeeping/ Cultivation	burnt stumps	None	occasional	frequent	heavily
			ashes	None	occasional	frequent	heavily
5	SN; 1, 2, 3 and 4	Human activities	foot paths	None	occasional	frequent	heavily

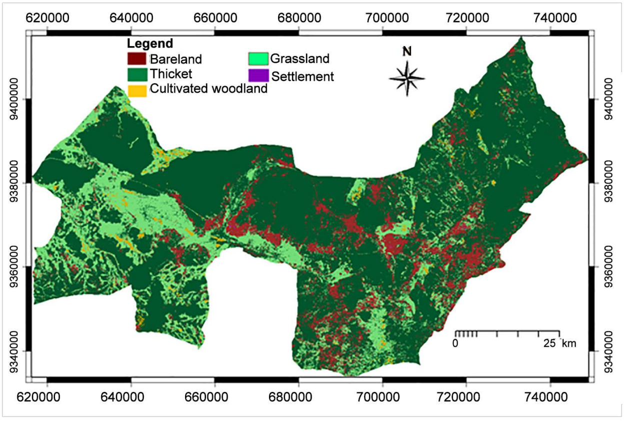
In addition, guided questions were administered to key informants (*i.e.* forest officers, village leaders and elders who lived in the area for more than 15 years) to capture an in-depth understanding of historical resources use pattern in the area.

3. Results

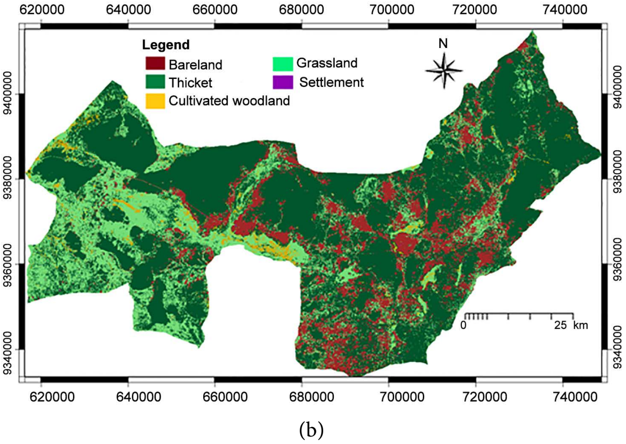
3.1. Itigi Thicket Land Covers Maps and Their Changes

The results from classification accuracy assessment revealed that the overall accuracy of classification for Itigi thicket was 81%. According to [24] the overall accuracy is acceptable if it is greater than 80%.

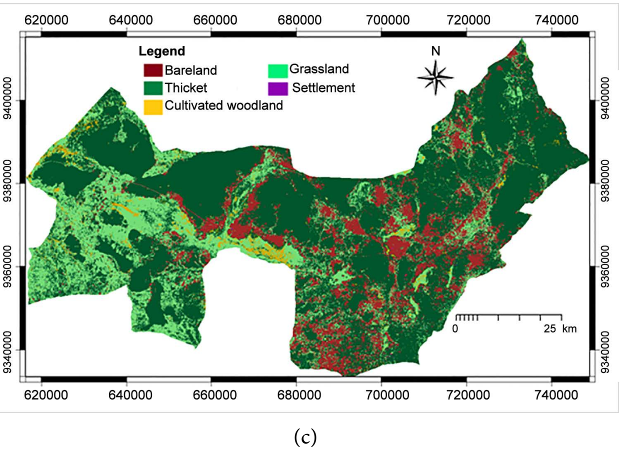
The land cover maps for the period 1991, 2000 and 2011 are presented in **Figure 2(a)**, **Figure 2(b)** and **Figure 2(c)**, while **Table 3** presents the cover areas for respective periods and the area changes between 1991/2000, and between 2000/2011 periods. The results showed that thicket occupies large area in Itigi thicket. For example in 1991, the area occupied by thicket was 345,150.5 ha (67.85 %), in 2000 was 313,451 ha (61.62%) and in 2011 was 293, 444.8 ha (57.7 %). Apparently, this large area occupied by thicket declined during 1991/2000 and 2000/2011. In 1991/2000, the area occupied by thicket declined by 31,699.5 ha (6.23%) while in 2000/2011 the area declined by 20,006.2 ha (3.93%). However, in 1991/2000 and 2000/2011 other land covers for example bare land increased by 3.64 % in both epochs, cultivated woodland increased by 0.89 % in 1991/ 2000 and 0.1% in 2000/2011. While settlement increased by 0.03% in 1991/2000 and 0.14% in 2000/2011. In 1991/2000; the area of grass land increased by 1.63%, and 0.13% in 2000/2011. Summary statistics for land cover changes are presented in Table 3.



(a)



(b)



(c)

Figure 2. (a) Land cover map of Itigi thicket for 1991; (b) Land cover map of Itigi thicket for 2000; (c) Land cover map of Itigi thicket for 2011.

Table 3. Cover area, change area and annual rate of change between 1991 and 2011 for Itigi thicket.

Land Cover Type	Land Cover						Change Area				Annual rate of change	
	1991		2000		2011		1991-2000		2000-2011		1991-2000	2000-2011
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	(ha/yr)	(ha/yr)
Bare Land	54282.4	10.67	73034.6	14.36	91603.6	18.0	18752.2	3.64	18569	3.64	2083.6	1688.1
Thicket	345150.5	67.85	313451	61.62	293444.8	57.7	−31699.5	−6.23	−20006.2	−3.92	−3522.2	−1818.7
Cultivated Woodland	5654.0	1.11	10153.1	2.00	10600.2	2.1	4499.1	0.89	447.1	0.1	499.9	40.6
Grassland	103447.6	20.34	111763.2	21.97	112184.4	22.1	8315.6	1.63	421.2	0.13	924.0	38.3
Settlement	161.6	0.03	294.3	0.06	862.9	0.2	132.7	0.03	568.6	0.14	14.7	51.7
Total	**508,696.1**	**100**	**508,695.9**	**100**	**508,696.1**	**100**						

3.2. Anthropogenic Activities Influencing Land Cover Changes in Itigi Thicket

Despite existence of many laws and by-laws enforced by Manyoni District Council (MDC), Tanzania Forest Services (TFS) and other stakeholders aiming at managing the Itigi thicket, anthropogenic activities still takes place. Table 4 shows the major causes of anthropogenic activities in the Itigi thicket. The causes differ considerably between the anthropogenic activities, for example the wood extract has a large number of causes as compared to other. The number of occurrence per ha of the causes for woody extract (Table 4) entails (28) for poles that are mainly being used as material for construction and firewood, (8) for charcoal kiln, (8) for logging and (5) for beekeeping. The wood clearing is attributable to farming (11) and sand stone mining (3), while presence of fodder and water (19) attracted animal grazing. The farm preparations, beekeeping activities and hunting (19) are largely causing wildfires in thicket while unplanned and planned activities such as woody tree clearing and livestock grazing are the major causes of trespassing (28) in Itigi thicket.

Poles extraction and firewood collection showed sign of highest moderate and severe anthropogenic activities compared to other anthropogenic activities (Figure 3). Results of analyses show significance difference (t-test, d. f = 20, $p < 0.05$) between frequency and the extent of anthropogenic activities within thicket area.

4. Discussion

Considering the five land-cover classes that were discriminated, *i.e.* thicket, grassland, bare land, cultivated woodland and settlement, the average overall accuracy of over 80%indicates the reliability of the classifications [25] thus giving confidence on the detected changes [28] [29] using a post-classification change detection of classified images (pixel-by-pixel comparison) providing change detection matrices [29] from which "from to" change class information was extracted. The change analysis has revealed that thicket cover declined from 345,150.5 ha in 1991 to 313,451 ha in 2000 and 293,444.3 ha in 2011. This reduction was also demonstrated by the increase of bare land from

Table 4. Anthropogenic activities, their causes and the number of occurrences in Itigi thicket.

SN	Anthropogenic activities	Main causes	No. of occurrence per ha
1	Woody extract	• Pole as material for construction and firewood collection	28
		• Logging	8
		• Charcoal kiln	8
		• Beekeeping-beehive making	5
2	Wood clearing	• Farms	11
		• Quarries (sand and stones)	3
3	Livestock grazing	• Fodder/water	19
4	Fires	• Hunting/Beekeeping/farms	19
5	Trespassing	• Woody tree clearing and grazing	28

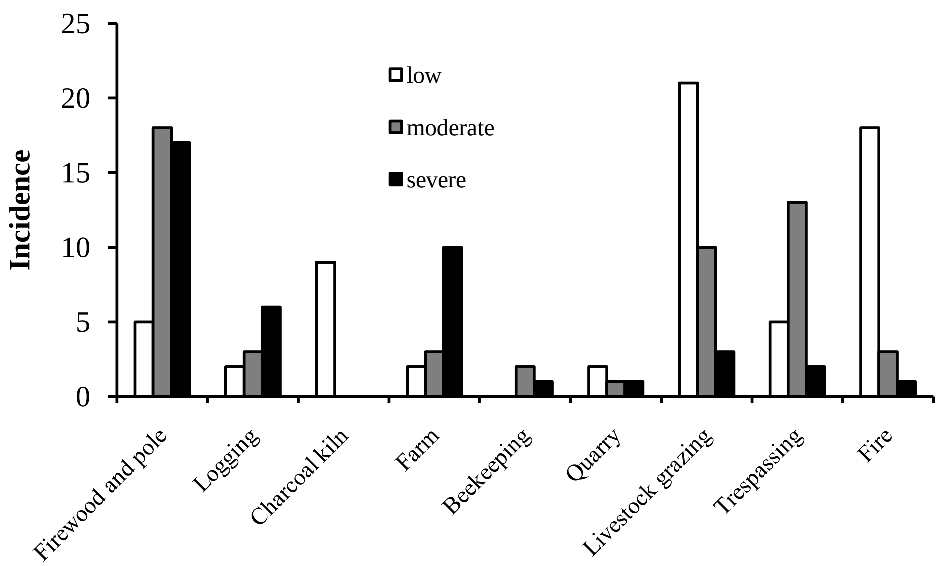


Figure 3. Extent of anthropogenic activities in Itigi thicket.

54,282.4 ha in 1991 to 73,034.6 ha in 2000 and 91,603.6 ha in 2011, cultivated woodland from 5,654 ha in 1991 to 10,153 ha 2000 and 10,600.2 ha in 2011 and settlement from 161.6 ha in 1991 to 294.3 ha in 2000 and 862.9 ha in 2011. Furthermore, thicket covers loss was also reflected in the mapped thicket area. These results are in agreement with [5] and [19] reports which showed the loss of Itigi thicket cover between 1990 and 2000.

The annual rate of change for thicket land cover between 1991 and 2000 was higher compared to that of 2000 to 2011. This estimate is in line with that reported by FAO FRA 2001 and 2010 which indicate considerable deforestation in the world during 1990-2010 [25]. For example in the Eastern and Southern Africa, deforestation rate per year was 1,841,000 ha in 1990-2000 and 1,839,000 ha in 2000-2010. Therefore there was considerable deforestation in the world during 1990-2010 but this was almost entirely confined to tropical regions [30]. The countries with the largest annual net loss for 1990-2000 were Nigeria (−3.67%), Indonesia (−1.75 %), Zimbabwe (−1.58%), Myanmar (−1.17%), Tanzania (−1.02%), Argentina (−0.88%), Sudan (−0.80%), Mexico (−0.52%), Brazil (−0.51%) and Congo (−0.20 %). The major causes of this loss in tropical forests include agriculture settlement, fires, overgrazing, logging and fuel wood [29].

Similarly, this study showed multi anthropogenic activities in Itigi thicket which associated with conversion of thicket to non-thicket areas. The major anthropogenic activities reported in this study include wood extract being caused by extraction of pole for construction and firewood collection, livestock grazing, charcoal burning and fires. Comparable results was reported by [31], that fires, cutting trees for fuel wood and poles, overgrazing and charcoaling are the major anthropogenic activities in Makurunge woodland. According to [32], clearing of forests in developing countries is mainly caused by agricultural expansion and inappropriate agricultural practices, overgrazing, charcoaling, fires, firewood gathering, commercial logging and industrial development. [33] showed that the forest ecosystem is increasingly threatened by anthropogenic activities such as agriculture and settlements, selective logging and fires. And the effects anthropogenic activities on forest structure and composition hinder forest regeneration [34].

Despite the few incidences of fire in Itigi thicket, the few occurrences are largely attributable to livestock grazing. According to [35], fire is an environmental factor affecting tropical savanna dynamics. Pattern of forests cover changes in Tanzania, suggests that fire has been the primary determinant of the vegetation dynamics [36]. Thus, the combined effects of both fire and livestock grazing probably pioneered other forms of activities such farming, firewood collection, charcoaling and logging. In addition, dependence by resource-poor households on cash income from the sale of thicket products appears to be the cause decline in thicket areas. Commercial production of firewood and charcoal as an alternative source of income to meet urban energy demands and curing tobacco contributes significantly to clearance of thicket. Since the available wood resources from Itigi thicket is almost constant, appropriate measures should be taken to overcome social interaction between people and available wood resources which bring about decline of thicket area for the sustainability of the wood resources.

Since the 1980s, sustainable forest management remains a challenge in Tanzania as manifested by the continued decline in forest cover. Results of Itigi land cover showed gradual change of thicket cover. It is therefore important to understand why thicket cover is declining. This understanding could go a long way in design of interventions for promotion of sustainable management. Furthermore, the need for accurate and reliable information about thicket cover change to inform debates, discussions and decision making on thicket management and conservation in Tanzania still exists [22].

And since this study reveals the potential of the widely reported national forest cover statistics either under-or over-estimating sub-national (local) forest cover changes, it is important that focus be extended to acquisition and reporting of sub-national (local) forest cover statistics. Making decisions with knowledge of local forest cover dynamics could potentially enhance sustainable forest management.

5. Conclusion and Recommendation

The study has revealed land cover changes in the Itigi thicket between 1991 and 2000 and between 2000 and 2011. This was an integrated assessment combining remote sensing and forest inventory approaches in understanding the land resources dynamics. The findings showed a decrease of thicket and increase of non-thicket area such as bareland, grassland, settlement and cultivated woodland due to anthropogenic activities including wood extract for fuel wood and construction, wood clearing for agriculture, livestock grazing, fires and trespassing. The study concludes that, there have been significant changes in land covers in the Itigi thicket. The study highlights the importance of integrating remote sensing and forest inventory in understanding the thicket resources dynamics and generating information that could be used to overcome the Itigi thicket problems for the sustainability of this unique vegetation.

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PAPER TWO

Models predicting above- and belowground biomass of thicket and associate tree species in Itigi thicket vegetation of Tanzania

Joseph Sitima Makero[a,c], Rogers Ernest Malimbwi[a], Tron Eid[b]and Eliakimu Zahabu[a]

[a] Department of Forest Resources Assessment and Management, Sokoine University of Agriculture, P.O. Box 3013, Morogoro, Tanzania

[b] Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, 1432 Ås, Norway

[c] Forestry Training Institute, Olmotonyi, P.O. Box 943, Arusha, Tanzania

*Corresponding author: Tel +0255 752 356 999/655 408 403

Email: makerojons@yahoo.com

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Models Predicting Above- and Belowground Biomass of Thicket and Associate Tree Species in Itigi Thicket Vegetation of Tanzania

Joseph Sitima Makero[1], Rogers Ernest Malimbwi[2], Tron Eid[3], Eliakimu Zahabu[2]

[1]Forestry Training Institute, Olmotonyi, Arusha, Tanzania

[2]Department of Forest Mensuration and Management, Sokoine University of Agriculture, Morogoro, Tanzania

[3]Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway

Email address:

makerojons@yahoo.com (J. S. Makero)

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Abstract: Itigi thicket is a unique vegetation type for Tanzania and is regarded as ecologically sensitive, thus earmarked for conservation. The objective of this study was to develop species-specific biomass models for two dominating thicket species and mixed-species biomass models for associate trees in Itigi thicket vegetation. Data were collected through destructive sampling (60 thicket clumps and 30 associate trees) and covered two dominant thicket species: *Combretum celastroides* Laws and *Pseudoprosopsis fischeri* (Tab) Harms and five dominant associate tree species: *Canthium burtii* Bullock sensu R. B. Drumm, *Cassipourea mollis* (R. E. Fr.) Alston, *Haplocoelum foliolosum* L, *Lannea fulva* (Engl.) England *Vangueria madagascariensis* J. F. Gmelin. Different nonlinear multiplicative model forms were tested, and models were selected based on Akaike Information Criterion. Large parts of the variation in biomass of thicket clumps were explained by basal area weighed mean diameter at breast height of stems in the clump and number of stems in the clump, i.e. for aboveground biomass (AGB) and belowground biomass (BGB) of *C. celastroides* up to 89% and 82% respectively and for AGB and BGB of *P. fischeri* up to 96% and 95% respectively. For associate trees most variation was explained by diameter at breast height (dbh) alone, i.e. up to 85% and 69% for ABG and BGB respectively. Although there will be some uncertainties related to biomass estimates for large areas, for practical reasons, we recommend the selected models to be applied to the entire area where Itigi thicket extends outside our study site, and also to those thicket and associate tree species present that were not included in the data used for modelling.

Keywords: Biomass Models, Above- and Belowground, Root Sampling, Root to Shoot Ratio

1. Introduction

Thicket is a dense formation of evergreen deciduous shrubs and low trees (2-5 m), often thorny and festooned with vines [1]. Thicket is generally influenced by soil type and structure, and is found in Africa, western Asia (e.g. Saudi Arabia, India), eastern and northern Australia and America (e.g. Mexico, central America, northern Argentina, central Bolivia, Paraguay, eastern Brazil) [2]. In eastern Africa, thickets extend from central Tanzania to the lowlands of the Somalia-Masai region all the way to Eritrea [3-4]. The climate of thicket's core area is semi-arid to sub-humid (rainfall 250-800 mm yr^{-1}) and subtropical to warm-temperate (largely frost-free). Thicket vegetation is dominated by trees and shrubs; they are very long-lived and are capable of sprouting after defoliation from herbivores, frost and fire [3].

Plant families and genera in thicket include Brassicaceae (*Boscia spp, Maerua spp*), Loganiaceae (*Strychnos spp*), Malvaceae (*Grewia spp*), Ochnaceae (*Ochna spp*), Rubiaceae (*Canthium spp*, *Psydrax spp, Xeromphis spp*), Rutaceae (*Clausena spp, Zanthoxylum spp*) and Euphorbiaceae (*Euphorbia spp*) [3]. Thicket supports a diverse mammal fauna, including for example African elephant, African buffalo, Burchell's zebra, kudu and eland [3, 5]. Thicket also offers both direct tangible benefits (e.g. fuel wood, construction and craft materials, medicines, food and fodder for animals) and indirect benefits including environmental services such as carbon sequestration, biodiversity, and soil and water conservation [5].

Itigi thicket (named from Itigi town in Manyoni district, Tanzania) is present in the semi-arid areas of the central parts in Tanzania. Itigi thicket extends from Manyoni district to Singida rural district and Bahi district in Dodoma region and is endemic to these areas. Itigi thicket covers an area of about 410,000 ha [6]. This vegetation type is unique in its occurrence, earmarked as ecologically sensitive for conservation and comprises about 12 thicket species and 15 associated tree species [5]. The dominant thicket species include *Pseudoprosopsis fischeri* (Tab) Harms,*Combretum celastroides* Laws and *Dicrostachys cinerea*.(L) Wight &Arn*,* while the dominant associate tree species in Itigi ticket vegetation include *Vangueria infausta* Burch*, Albizia petersiana* (Bolle) Oliv*, Canthium burtii*Bullock sensu R. B. Drumm *and Cassipourea mollis* (R. E. Fr.) Alston [6]. A recent sample plot inventory in the area showed that *P. fischeri* and *C. celastroides* contribute more than 50% of all stems (unpublished results).

Quantifying amounts of biomass and carbon for different forest types has recently become important all over the world [7-10]. Among others, it is central to the implementation of the carbon credit market mechanism Reducing Emission from Deforestation and Forest Degradation (REDD+) in developing countries. Biomass of trees can be estimated either by means of stem volume and biomass expansion factors, or by applying biomass models. Typically, biomass models predict biomass by means of easily measureable tree parameters like as diameter at breast height (dbh) and total tree height (ht). Provided information on individual trees is available, biomass models is generally a more accurate way to quantify the amount of biomass than using biomass expansion factors.

Biomass models are also useful tools in assessing forest structure and conditions. They may provide information on supply of industrial wood, biomass for domestic energy and even on availability of animal fodder from the forest. Biomass models are also relevant as parts of remote sensing forest inventory applications and for field inventories related to conventional forest management planning. In recent years, various biomass and volume models have been developed in sub-Saharan Africa. A review report describing such models from sub-Saharan Africa [11] shows that biomass and volume models are unevenly distributed among vegetation types. While for example 43% of the biomass models and 63% of the volume models were developed for tropical rainforests, only 16% of the biomass models and 23% of the volume models were developed for shrub-land.

In Tanzania, biomass models have previously been developed for miombo woodland [12-15]. A few models estimating biomass of shrubs in subtropical thicket in south-east Africa have been reported [16]. However, no biomass models have been documented for thicket vegetation in Tanzania, and the need for the development of such models is therefore obvious. This is of particular importance since Tanzania recently has established a national forest inventory (National Forest Resources Monitoring and Assessment, NAFORMA) to monitor the woodlands and forests of the entire country [17].

The objective of this study was to develop species-specific biomass models for two dominating thicket species and mixed-species biomass models for associate trees in Itigi thicket vegetation in Tanzania. Models for aboveground, belowground and total biomass models were developed. Statistics on the root to shoot ratio (RS-ratio) are also presented.

2. Materials and Methods

2.1. Site Description

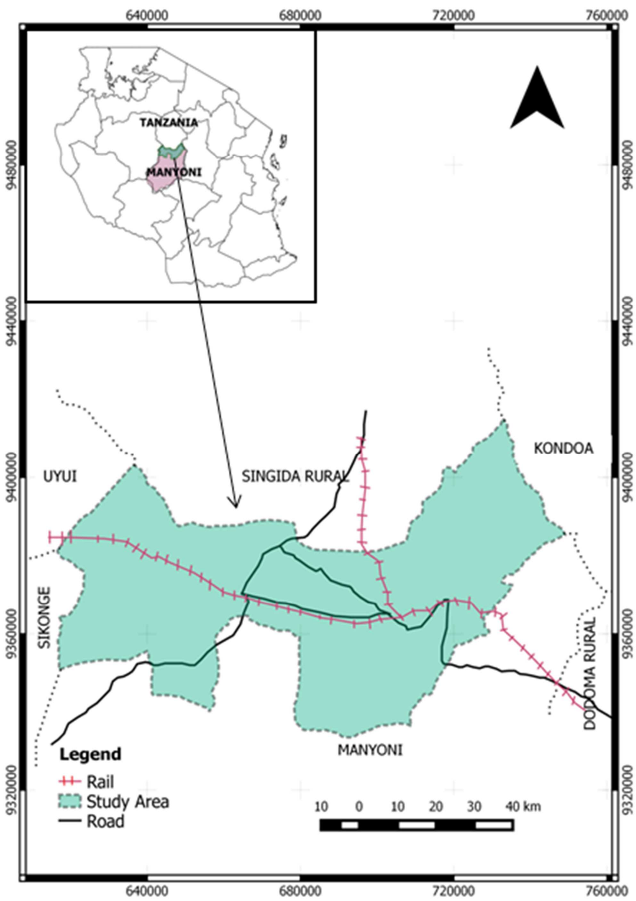

Figure 1. *Location of the study site.*

The study site was located in the northern part of Manyoni district in Singida region (5°31' to 5°50'S and 34°31' to 34°49'E) (Figure 1). The site is located between 1,244 m and 1,300 m above mean sea level [6]. This area has three distinct seasons; a cool dry season from May to August, a hot dry season from August to November, and a rainy season from November through April. Manyoni district has a unimodal distribution in rainfall, the average number of rainy days is 49 per year and the mean annual rainfall is 624 mm in the higher altitudes of Manyoni district where majority of thickets are found. The monthly temperature of the area varies from 19°C in July to 24.4°C in November.

Geologically, the area is underlain by a basement floor of granite. The soil is not stony and thereby favours the root systems of thicket species [4, 18]. Itigi thicket is floristically rich and dominated by *P. fischeri* and *C. celastroides.* Other thicket species includes; *Craibia abbreviata* subsp. burtii, *Combretum paniculatum*. Vent, *D. cinerea*, *Croton scheffleri* Pax, *Excoecaria bussei* (Pax) Pax, *Grewia forbesii* Harv. ex Mast, *Grewia similis* K. Schum, *Ochna ovata* F. Hoffm, *Rinorea angustifolia* Grey-Wilson, *Tennantia sennii* (Chiov.) Verdc. & Bridson, and *Zanthoxyllum chalebium* Engl [6]. Within the Itigi thicket vegetation there are also small trees (associate trees) such as *Acacia tortilis* (Forsk.) Hayne, Arzeyk*., Baphia massaiensis* Taub*., C. mollis, H. foliolosum, L. fulva, Senna singueana* (Delile) Lock*, Maerua triphylla* A. Richand *V. madagascariensis*. In addition, there are also small patches of miombo woodlands composed of miombo dominants such as *Brachystegia boehimii* Benth*, Brachystegia spiciformis* Benth*, Julbernadia globiflora* (Benth) and *Burkea africana* Hook [5-6].

2.2. Sampling Thicket Clumps and Associate Trees

As a basis for biomass models, 60 clumps of two dominant thicket species (30 clumps of *P. fischeri* and 30 clumps of *C. celastroides*) and 30 associate trees were sampled. A thicket clump here refers to a close group of stems originating from the same root sucker. Associate trees refer to a small trees (usually with a dbh below 20 cm and height below 8 m) found scattered in thicket stand and tending to grow up when the thicket canopy cover is reduced to below 40%.

The fieldwork was carried out in two stages. The first stage involved a reconnaissance survey in order to become acquainted with the study site, delineate thicket boundaries and stratify the thicket area into either open thicket or closed thicket. Open thicket here refers to an area with thicket cover below 50% and closed thicket is an area with thicket cover above 50%. The second stage involved establishment of plots for selecting thicket clumps and associate trees. From a map displaying the thicket vegetation we randomly selected coordinates for 30 plots in the two strata open and closed thicket vegetation, respectively. The coordinates of the plot centres were located in the field using a hand held GPS. The plot size was 154 m^2 (7 m radius). For each stratum (open and closed), 15 clumps of each of the two thicket species and 15 associate trees were selected.

Within each plot, two clumps of each thickets species and one associated tree were selected for destructive sampling. We selected the two clumps from the respective species with more than 5 stems that were closest to the plot centre. Among the associate tree species we selected the closest tree to the plot centre. If an associate tree was not found inside the plot, the closest tree to the plot centre outside the plot was selected.

Before felling, the thicket species was identified, the number of stems in the clump (stem count, i.e. st) was recorded and all stems measured for diameter at breast height (dbh) using a calliper. In addition, the total height of tallest stem (ht) in a clump was measured. For each clump, a basal area weighed mean diameter at breast height of stems (dbh_w) was computed in the following way;

$$dbh_W = \sqrt{\frac{\sum BA_i \times 4}{st \times 3.14159}}$$

where BA_i is basal area of the i^{th} stem in a clump.

Similarly, for each selected associate tree, the tree species was identified and measurements of dbh and ht taken. Table 1 and 2 show statistical summaries of the selected thicket clumps and associated trees.

Table 1. *Statistical summary for selected thicket clumps.*

Species	n	Basal area weighted mean dbh (cm)			Height (m)			Number of stems in a clump		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Combretum celastroides	30	2.4	1.5	3.2	4.5	3.5	6.5	15	6	29
Pseudoprosopis fischeri	30	2.2	1.2	3.0	4.1	3.0	6.0	22	9	57

n= number of thicket clumps, min=minimum, max=maximum

Table 2. *Statistical summary for selected associate trees.*

Species	n	Diameter at breast height (cm)			Height (m)		
		Mean	Min	Max	Mean	Min	Max
Canthium burtii	2	7.4	7.3	7.5	5.5	5.0	6.0
Cassipourea mollis	2	10.2	9.9	10.4	7.2	6.9	7.5
Haplocoelum foliolosum	8	10.7	6.1	18.0	5.9	5.0	7.0
Lannea fulva	6	10.8	10.1	11.7	5.3	5.0	6.0
Vangueria madagascariensis	12	10.0	7.0	15.2	6.2	5.0	7.2
All	30	10.0	6.1	18.0	6.0	5.0	7.5

n= number of trees, min=minimum, max=maximum

2.3. Destructive Sampling and Laboratory Procedures

We first divided the thicket clumps into above- and belowground components. The aboveground component was considered as all biomass above a stump height of 10 cm. It was divided into; main stems (diameter > 2 cm), branches (diameter ≤ 2 cm and ≥ 1 cm) and twigs (diameter < 1 cm). Leaves and sawdust from cutting were not included in biomass because the thicket had started to shed them when we carried out the destructive sampling and sawdust mainly because of the workload associated with collecting sawdust from ground. The main stems, branches and twigs were separated into bundles and their green weights were weighed using a spring balance. For each selected clump, three sub-samples from main stems, branches and twigs, respectively, were measured for green weight using an electronic balance. Finally, all sub-samples were labelled and prepared for laboratory analyses.

For all thicket clumps, the root crown and all roots originating from root crown were excavated up to a minimum diameter of 0.5 cm (located 1.0 to 1.5 m from centre of root crown). Then the root crown and roots were pulled from the soil, and subsequently tightened into a bundle, cleaned for soil and weighed. Three sub-samples were taken from root crown and one from root bundle.

The associate trees were also divided into above- (biomass above a stump height of 10 cm) and belowground components. The aboveground component was divided into main stem (diameter > 5.0 cm), branches (diameter ≤ 5.0 cm and ≥ 2.5 cm) and twigs (diameter < 2.5 cm). Leaves and husks were not included. Stem, branches and twigs were trimmed and cross cut into manageable billets ranging from 1 to 2.5 m in length their green weights were determined. Finally, three sub-samples from main stems, branches and from twigs were taken and measured for green weight.

For the belowground component of associate trees we applied a root sampling procedure [14]. We first excavated until all main roots initiating from the root crown were visible. Then three main roots (largest, medium and smallest) originating from the root crown were selected and excavated in full (including up to three side roots) until the point where their diameters were 1 cm. These main roots were measured for basal diameter (diameter at the branching point from the root crown) and then weighed. During the process, up to three side roots were selected from the excavated main roots and measured for basal diameter (diameter at the branching points from the main root) and then weighed. The remaining side roots from the excavated main roots were measured for basal diameter. For each tree, three sub-samples were taken from root crown, main roots and side roots respectively, and then measured with an electronic balance for green weight.

In the laboratory, all collected above- and belowground sub-samples were oven dried to a constant weight at 70°C for at least 48 hours and then the weight was monitored at intervals of 6 hours until there was no change. Finally, biomass was determined with an electronic balance.

2.4. Determination of Observed Biomass Dry Weight

For the aboveground component of thicket clumps and associate trees, we computed tree- and component specific (stems, branches and twigs) dry to green weight ratios (DG-ratios) based on the sub-samples. The biomass of all components of a clump or tree was then obtained as the product of DG-ratios and green weight of the respective thicket clump and associate tree components. The AGB weight was computed as the sum of stems, branches and twigs.

For the belowground component of thicket clumps, we first converted green weights from root crown and roots into biomass as the product of the DG-ratio and their green weights. The BGB was computed as the sum of root crown and roots.

For the belowground component of associate trees, we also first converted green weights from all excavated parts of root crown, main roots and side roots into dry weight biomass as the product of the DG-ratios and their green weights. Then the following procedure was applied;

A side root model (n = 123 side roots) was developed by regressing biomass and basal diameter of the side roots. The side root model was as follows:

$$B = 0.091 \times D^{1.740};\ RMSE=0.125;\ R^2=0.70;\ MPE_r= -1.02$$

where B is side root biomass (kg) and D is basal diameter of side root (cm). RMSE is Root Mean Square Error (kg), R^2 is coefficient of determination and MPE_r is relative mean prediction error (%). MPE_r was not significantly different from zero.

This side root model was applied to predict biomass of all side roots not excavated. To determine total biomass of the selected main roots, the predicted biomass of side roots not excavated were added to the biomass of excavated side roots and those parts of the main root that were excavated. Then, main root models were developed by regressing total biomass and basal diameter of selected main roots. The model (n = 90 main roots) for the main roots was as follows:

$$B = 0.504 \times D^{0.668};\ RMSE=0.293,\ R^2=0.54,\ MPE_r=-0.39$$

where B is main root biomass (kg) and D is basal diameter of main root (cm). MPE_r was not significantly different from zero.

Finally, the main root model was applied to predict biomass of unexcavated main roots originating from the root crown. The BGB was computed as the sum of all predicted and measured main root biomass and the biomass of the root crown. Scatter plots of AGB and BGB versus diameter (dbh_w and dbh) for individual thicket clumps and associate trees are presented in Figures 2 and 3.

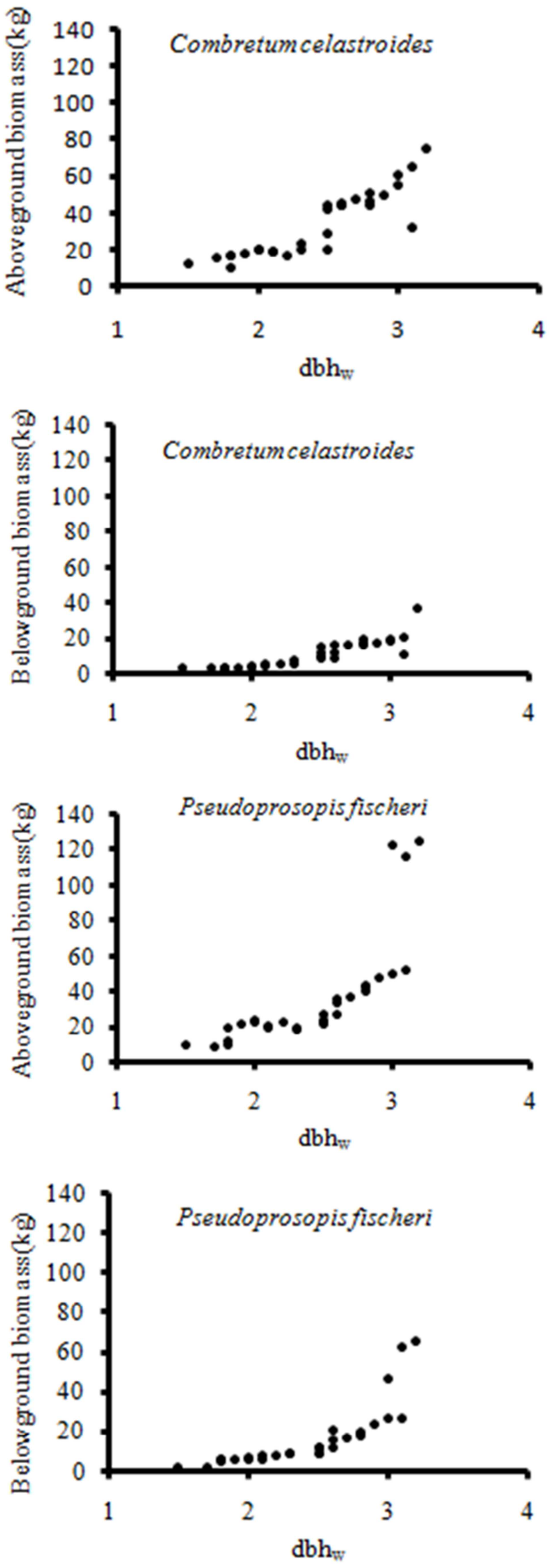

Figure 2. *Scatter plots of AGB and BGB versus* dbh_w *for individual thicket clumps.*

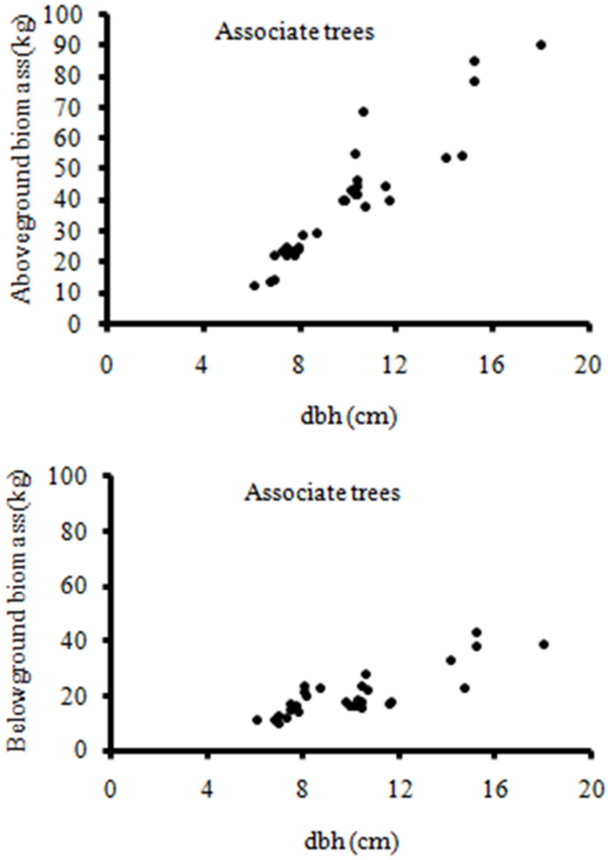

Figure 3. *Scatter plots of AGB and BGB versus dbh for associate trees.*

2.5. Model Development, Selection and Evaluation

For the thicket clumps, two models were tested, i.e. model 1 with dbh_w and st as independent variables and model 2 with dbh_w, ht and st as independent variables. Also for the associate trees, two models were tested, i.e. model 3 with dbh only and model 4 with dbh and ht as independent variables. The tested model forms (multiplicative) are commonly used to develop biomass models in the literature [9-10].

$B = \beta_0 \times dbh_w^{\beta 1} \times st^{\beta 2}$(model 1)

$B = \beta_0 \times dbh_w^{\beta 1} \times ht^{\beta 2} \times st^{\beta 3}$(model 2)

$B = \beta_0 \times dbh^{\beta 1}$(model3)

$B = \beta_0 \times dbh^{\beta 1} \times ht^{\beta 2}$(model 4)

where B is AGB or BGB or total biomass (TB), β_0, β_1, β_2 and β_3 are model parameters.

The PROC NLN procedure in SAS software [19] was used to estimate the model parameters (β_0, β_1, β_2, and β_3). The procedure produces the least squares estimates of the parameters of a nonlinear model through an iteration process.

The selection of final models was in general based on the Akaike Information Criterion (AIC). AIC takes into account the number of parameters in the models and penalize them accordingly. However, if a model had insignificant parameter estimates, it was not considered further. The coefficient of determination (R^2) and Root Mean Squared Error (RMSE) were reported for all models. In addition, the relative Mean

Prediction Error (MPE_r) was reported for each model as:

$$MPE_r = \left(\frac{100}{n}\right) \times \sum \left[\frac{y_i - \hat{y}_i}{\bar{y}}\right],$$

where y_i is observed biomass of clump/tree i, $\hat{y}_i$ is predicted biomass of clump/tree i, $\bar{y}$ is the mean of observed biomass, and n is the number of clumps/trees. Paired *t*-tests were employed for testing if MPE was significantly different from zero.

3. Results

Root to shoot ratios (RS-ratios) for thicket species and associated trees are presented in Table 3. The mean RS-ratios for *C. celastroides* and *P. fischeri* were 0.38 and 0.51, respectively, and they were significantly different ($p = 0.04383$). The RS-ratios both thicket species were not significantly different between dbh-classes; *C. celastroides* ($p = 0.4295$) and *P. fischeri* ($p = 0.3967$). The mean RS-ratio for the associate trees was 0.41. For these trees, the RS-ratio was significantly different between dbh-classes ($p < 0.000$).

Table 3. *Root to shoot ratio (RS-ratio) over species and diameter classes.*

Species	Dbh-class	n	RS-ratio			
	(cm)		Mean	Min	Max	STD
Combretum celastroides	- 2.1	10	0.44	0.17	0.71	0.18
	2.2 - 2.6	10	0.34	0.16	0.51	0.12
	2.7 -	10	0.35	0.16	0.54	0.13
	All	30	0.38	0.16	0.71	0.15
Pseudoprosopsis fischeri	- 1.9	11	0.57	0.21	0.92	0.25
	2.0 - 2.4	10	0.48	0.29	0.67	0.14
	2.5 -	9	0.46	0.31	0.60	0.11
	All	30	0.51	0.21	0.92	0.18
Associate trees	- 8.0	11	0.57	0.27	0.88	0.20
	8.1 - 10.4	10	0.30	0.14	0.45	0.12
	10.5 -	9	0.34	0.16	0.51	0.13
	All	30	0.41	0.14	0.88	0.16

Parameter estimates and performance criteria for the two thicket species models are summarized in Table 4. For AGB of *C. celastroides*, both models had significant parameter estimates. Since model 2 provides the lowest AIC, this was selected for further analyses (bold in Table 4). For BGB, the parameter estimates were not consistently significant for any of the two models. However, since model 1 has signs as expected in the parameter estimates for dbh_w and st, i.e. increasing biomass with increasing dbh_w and st, we still considered this model as valid and selected it for further analyses. For total biomass (TB) of *C. celastroides*, model 1 was selected since model 2 has insignificant parameter estimates. For *P. fischeri*, none of the models including ht as independent variable (model 2) consistently have significant parameter estimates. For all components of this species, model 1 was therefore selected for further analyses.

Parameter estimates and performance criteria for the associate tree models are summarized in Table 5. For all biomass components, no models including ht as independent variable (model 4) had consistently significant parameter. Model 3 was accordingly selected (bold in Table 5) for further analyses for all biomass components.

Table 4. *Parameter estimates and performance criteria of biomass models for thicket species.*

Species	Component	Model	Parameter estimates				RMSE (kg)	R^2	MPE_r (%)	AIC
			b_o	b_1	b_2	b_3				
Combretum celastroides	AGB	1	0.877373	2.956328	0.356776		6.510	0.89	0.18	200.38
		2	0.726938	2.670954	0.573718	0.203860	6.030	0.90	-0.21	196.65
	BGB	1	0.106055*	4.006166	0.349925		3.526	0.82	-0.16	163.59
		2	0.083440*	3.462122	1.033348*	0.047325*	3.202	0.85	-0.61	196.65
	TB	1	0.914780	3.211717	0.355552		9.141	0.90	0.14	220.74
		2	0.745887	2.866816	0.679345	0.169968*	8.234	0.91	-0.32	215.96
Pseudoprosopis fischeri	AGB	1	0.427622	3.405307	0.52902		6.699	0.96	1.75	202.09
		2	0.383697	3.373528	0.132574*	0.511206	6.793	0.96	1.72	203.79
	BGB	1	0.144225	4.153442	0.411693		3.853	0.95	1.06	168.90
		2	0.164340*	4.205059	0.16898*	0.433325	3.908	0.95	1.14	170.63
	TB	1	0.572087	3.642461	0.488888		9.259	0.96	1.54	221.51
		2	0.550836	3.630150	0.047091*	0.482675	9.429	0.96	-0.10	223.47

*Parameter estimate not significant ($p > 0.05$), selected models in bold

Table 5. *Parameter estimates and performance criteria of biomass models for associate tree species.*

Component	Model	Parameter estimates			RMSE (kg)	R^2	MPE_r (%)	AIC
		b_o	b_1	b_2				
AGB	3	1.201291	1.507567		8.086	0.85	-0.55	212.48
	4	0.755707*	1.368491	0.436371*	8.024	0.86	-0.45	212.92
BGB	3	1.380314	1.167124		4.732	0.69	0.22	180.33
	4	0.530607*	0.883575	0.895054	4.384	0.74	0.39	176.65
TB	3	2.341904	1.400620		10.552	0.86	-0.20	228.45
	4	1.236287*	1.210285	0.599351*	10.021	0.88	-0.05	226.26

*Parameter estimate not significant ($p > 0.05$), selected models in bold

The selected models for thicket clumps were further evaluated over dbh-classes by means of relative mean prediction error (MPE_r) (Table 6). Based on all observations, MPE_r were not significantly different from zero for any species or components. Furthermore, for *C. celastroides*, MPE_r were not significantly different from zero for any of the dbh-classes. For *P. fischeri*, however, MPE_r was significantly different from zero for some of the dbh-classes.

The predicted biomass when applying the AGB and BGB models separately summarized to 45.34 kg and 52.80 kg for *C. celastroides* and *P. fischeri*, respectively, while the corresponding predicted biomass when applying the TB models were 45.20 kg and 52.79 kg (Table 6).

The evaluations of the selected associate tree models (Table 7) showed that overall for all observations, MPE_r was not significantly different from zero for any of the components. However, for both the AGB and BGB models, MPE_r was significantly different from zero in the smallest dbh-class. For the associate trees, the summarized predicted biomass when applying the AGB and BGB models separately was 60.51 kg while the corresponding predicted biomass when applying the TB model was 60.48 kg.

Table 6. *Evaluation of selected models for thicket clumps.*

Species	Component	Model	dbh-class (cm)	n	Biomass (kg)		MPE_r (%)	P-value
					Observed	Predicted		
Combretum celastroides	AGB	2	-2.1	10	16.66	15.90	0.74	0.3957
		2	2.2-2.6	10	32.92	33.44	-0.51	0.8269
		2	2.7-	10	52.61	53.05	-0.44	0.7961
		2	All	30	34.06	34.13	-0.21	0.9428
	BGB	1	-2.1	10	3.63	3.57	0.19	0.8484
		1	2.2-2.6	10	10.41	10.38	0.07	0.9730
		1	2.7-	10	19.55	19.69	-0.42	0.9308
		1	All	30	11.20	11.21	-0.16	0.9748
	TB	1	-2.1	10	20.29	18.61	1.24	0.2686
		1	2.2-2.6	10	43.33	44.20	-0.64	0.7522
		1	2.7-	10	72.16	72.78	-0.45	0.8579
		1	All	30	45.26	45.20	0.14	0.9660
Pseudoprosopis fischeri	AGB	1	-1.9	11	17.64	13.67	3.94	0.0122
		1	2.0-2.4	10	27.00	30.77	-3.41	0.0384
		1	2.5-	9	71.41	69.92	1.21	0.5763
		1	All	30	36.89	36.25	1.75	0.5864
	BGB	1	-1.9	11	5.76	4.96	1.75	0.0228
		1	2.0-2.4	10	12.88	13.17	-0.58	0.7312
		1	2.5-	9	34.40	34.46	-0.10	0.9790
		1	All	30	16.73	16.55	1.06	0.7953
	TB	1	-1.9	11	23.40	18.54	3.32	0.0075
		1	2.0-2.4	10	39.88	43.99	-2.55	0.0490
		1	2.5-	9	105.81	104.43	0.77	0.7570
		1	All	30	53.62	52.79	1.54	0.6142

Table 7. *Evaluation of selected models for associate tree species.*

Component	Model	dbh-class (cm)	n	Biomass (kg)		MPE_r (%)	P-value
				Observed	Predicted		
AGB	3	-8	11	20.90	24.30	-3.12	0.0026
	3	8.1-10.4	10	41.15	37.80	2.79	0.3417
	3	10.5-	9	61.42	61.70	-0.22	0.1380
	3	All	30	39.81	40.00	-0.55	0.8812
BGB	3	-8	11	15.15	14.14	1.81	0.0413
	3	8.1-10.4	10	18.70	19.92	-1.98	0.3420
	3	10.5-	9	29.22	28.96	0.38	0.9450
	3	All	30	20.55	20.51	0.22	0.9577
TB	3	-8	11	36.05	38.24	-1.33	0.9473
	3	8.1-10.4	10	59.85	57.69	1.19	0.9085
	3	10.5-	9	90.64	90.77	-0.07	0.9833
	3	All	30	60.36	60.48	-0.20	0.9488

4. Discussion

The biomass models presented in this study are the first ones developed for thickets in Tanzania. We focused on the two dominant thicket species (*C. celastroides* and *P. fischeri*), mainly because of limited resources to cover all the thicket species present in Itigi thicket. The selection of thicket clump data for modelling the two species was based on randomly distributed sample plots within the study site to secure the clumps to be as representative as possible. Also within each plot, the thicket clumps were selected randomly. Thus, clumps with wide ranges regarding different sizes were covered, i.e. dbh_w ranged from 1.2 cm to 3.2 cm, ht from 3 m to 6.5 m and st from 6 to 57 (Table 1). Use of modelling data with appropriate numbers of both small and large clumps is important in order to avoid extrapolation, and the uncertainty related to this, as much as possible.

The number of sampled thicket clumps for each species was relatively small (30) compared to for example recently developed biomass models for miombo woodlands and mangrove forest in Tanzania [14-15, 20]. However, a large number of previously developed models in sub-Saharan Africa have also used fewer observations than in the present study [11].

Leaves were excluded from our AGB because the clumps had started to shed leaves when we carried out destructive sampling. This is a common challenge for biomass studies in seasonally dry forests as acknowledged by [10]. A recent study for miombo woodlands in Mozambique by [21] found that leaves comprised only 3% of the AGB during the peak leaf season. Such a number would probably also be a good estimate of how much AGB that is missing in our data. We also decided not to include sawdust from cutting stems into billets, mainly because of the workload associated with collecting sawdust from ground. However, although this will lead to an observed biomass that is lower than reality, sawdust constitute a very small part of the total biomass (<0.3%) [14].

The mean RS-ratios of the sampled thicket clumps varied between the species, i.e. for *C. celastroides* and *P. fischeri,* they were 0.38 and 0.51, respectively (Table 3). The difference in RS-ratio could be due to real morphological differences between the two species, but also due to differences in size for the sampled clumps between the two species (Table 1). The RS-ratios reported, however, is not unique for thicket as similar levels have been reported in Tanzania for miombo woodlands [14] and mangrove forest [20].

Generally for the thicket clumps, large parts of the variations in biomass were explained by dbh_w and st while ht explained variations only marginally. For *P. fischeri*, none of the component models with ht as independent variable (model 2) consistently had significant parameter estimates. The obvious choice for this species was therefore model 1 with dbh_w and st (Table 4). For *C. celastroides*, the selection of appropriate models was more complicated. For AGB, model 2 was selected while for TB model 1 was selected since these models had consistently significant parameter estimates and low AIC values. For BGB of *C. celastroides*, however, no models consistently had significant parameter estimates. Since separate estimation of BGB sometimes may be useful also for this species, we recommend the use of model 1 because the signs of the parameter estimates were as expected. The relevance of such a recommendation is also supported by the evaluation of this model that revealed an appropriate performance with no significant differences between observed and predicted biomass (Table 6).

The presented models for thicket clumps are meant to be applied, based on forest inventories, for estimating biomass per area unit or in total for a certain forest area. The most accurate biomass estimate will of course be achieved by measuring dbh of all stems in the clumps. However, since measuring dbh of all stems is time consuming, an alternative could be to measure dbh of for example the smallest, a medium and the largest stem regarding dbh in a clump, and then apply the dbh_w of these three stems as input for the models. Such a procedure will of course increase the uncertainty in the biomass estimates when applying the models, but it will also reduce time consumption in practical inventories considerably.

The species-specific thicket clump models developed may generally be applied inside the study site (Manyoni). The models may also be applied outside this site where Itigi thicket extends (i.e. Singida rural district and Bahi district in Dodoma region) because growing conditions here are very similar. Although Itigi thicket comprise of more than 10 different species, a recent sample plot inventory in the area showed that the two selected species contribute to more than

50% of the total stem density (Unpublished results). For practical reason when estimating biomass for larger areas we therefore recommend the models to be applied also to remaining thickets species with similar morphology. The uncertainty in biomass estimates will of course increase by doing this, but this is the only option since models do not exist for the remaining species.

The selection of associate trees for modelling was also based on randomly distributed sample plots to secure the associate trees to be as representative as possible. Within each plot, an associate tree was also selected randomly. Thus, associate trees with wide ranges regarding different sizes were covered, i.e. dbh ranged from 6.1 cm to 18 cm (Table 2). Five different tree species (*C. burtii, C. mollis, H. foliolosum, L. fulva* and *V. madagascariensis*), out of a total of 15 tree species, were selected. Since the trees were selected randomly, the five species will comprise a large part of the biomass in the area, and as such, the uncertainty related to the relatively few species included in the mixed-species models will be relatively low when applying them also to the remaining species.

The average RS-ratio for the associate trees was 0.41, which is similar with what was reported for miombo woodlands in Tanzania [14]. The RS-ratio varied significantly between dbh classes with a high RS-ratio for small trees and lower RS-ratios for larger trees (Table 3). A similar pattern for miombo woodland trees was observed by [22] who found that the RS-ratio was decreasing significantly and non-linearly with increasing dbh. The use of RS-ratio is recommended for estimating belowground biomass in cases where models are not available [23] and mean RS-ratios are frequently applied to estimate belowground biomass [24]. However, by using a fixed mean RS-ratio for a relationship that most probably is non-linear, a bias will be introduced. Therefore, application of mean RS-ratios to estimate belowground biomass should be done with caution, and avoided if BGB models exist.

Generally for the associate trees, large parts of the variations in biomass were explained by dbh while ht explained variations in biomass only marginally. None of the selected mixed-species models for associate trees included ht as independent variable (Table 5). Model 3 with dbh only as independent variable was therefore selected for all biomass components. The application recommendations for these models are similar to those of the thicket clumps; for the study site, and outside where the Itigi ticket vegetation extends.

5. Conclusions

The developed species-specific models for thicket and mixed-species models for associate trees were based on a comprehensive and well-documented set of data comprising dominant thicket and associate tree species. The model fitting showed that large parts of the variation in biomass of thicket were explained by basal area weighed mean diameter at breast height and number of stems in the clumps while for associate trees most variation was explained by diameter at breast height only. Although there will be some uncertainties related to biomass estimates for large areas, for practical reasons, we recommend the selected models to be applied to the entire area where Itigi thicket extends outside our study site, and also to those thicket and associate tree species present that were not included in the data used for modelling.

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Appendix. Sample Clumps and Associate Trees Used to Develop Biomass Models and Their Respective Names and Sizes

Table A1. *Thicket clumps.*

Combretum celastroides			***Pseudoprosopsis fischeri***		
dbh_w (cm)	**ht (m)**	**st**	**dbh_w (cm)**	**ht (m)**	**st**
1.5	4.5	15	1.2	4.0	20
1.7	4.4	12	1.5	3.5	18
1.8	4.0	9	1.6	3.0	12
1.8	4.5	29	1.7	4.0	36
1.8	5.0	27	1.7	4.0	23
1.9	4.5	8	1.7	4.0	13
2.0	4.4	14	1.8	4.0	25
2.0	4.4	11	1.8	4.5	31
2.1	3.9	13	1.9	4.5	18
2.1	4.0	25	1.9	3.5	16
2.2	4.8	29	1.9	3.0	16
2.3	4.0	12	2.0	4.5	20
2.3	4.4	8	2.1	4.0	22

Combretum celastroides			*Pseudoprosopsis fischeri*		
dbh_w (cm)	**ht (m)**	**st**	**dbh_w (cm)**	**ht (m)**	**st**
2.5	3.5	13	2.1	5.5	38
2.5	4.3	10	2.1	3.0	18
2.5	4.4	21	2.1	4.5	19
2.5	6.5	25	2.1	3.0	17
2.6	4.3	10	2.2	4.5	16
2.6	3.5	20	2.3	4.0	21
2.6	5.2	17	2.4	6.0	17
2.7	5.0	19	2.4	3.5	22
2.8	4.5	17	2.5	4.5	13
2.8	4.3	8	2.5	4.0	19
2.8	4.2	17	2.5	4.0	13
2.9	4.5	10	2.7	4.0	10
3.0	5.0	12	2.7	4.0	21
3.0	5.6	18	2.8	5.0	57
3.1	4.9	14	2.8	4.5	42
3.1	3.5	6	2.9	4.0	9
3.2	5.2	13	3.0	5.0	38

Table A2. *Associate trees.*

Scientific name	dbh (cm)	ht (m)
Haplocoelum inopleum	6.1	6.0
Haplocoelum inopleum	6.8	6.0
Haplocoelum inopleum	7.0	5.2
Vangueria madagascariensis	7.0	5.0
Canthium burtii	7.3	5.0
Canthium burtii	7.5	6.0
Haplocoelum inopleum	7.5	5.0
Vangueria madagascariensis	7.7	5.0
Vangueria madagascariensis	7.8	5.3
Vangueria madagascariensis	8.0	6.0
Vangueria madagascariensis	8.0	5.0
Vangueria madagascariensis	8.1	7.0
Vangueria madagascariensis	8.7	7.0
Vangueria madagascariencies	9.8	6.0
Cassipourea mollis	9.9	6.9
Lannea fulva	10.1	5.0
Haplocoelum inopleum	10.3	6.0
Haplocoelum inopleum	10.3	5.1
Lannea fulva	10.4	5.5
Cassipourea mollis	10.4	7.5
Lannea fulva	10.4	5.0
Lannea fulva	10.6	5.0
Vangueria madagascariencies	10.7	7.0
Lannea fulva	11.6	6.0
Lannea fulva	11.7	5.5
Vangueria madagascariensis	14.1	7.0
Haplocoelum inopleum	14.7	6.7
Vangueria madagascariensis	15.2	7.2
Vangueria madagascariensis	15.2	7.2
Haplocoelum inopleum	18.0	7.0

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PAPER THREE

Models for prediction of volume of thicket and associate tree species in Itigi thicket vegetation of Tanzania

Joseph Sitima Makero[a,c], Rogers Ernest Malimbwi[a], Eliakimu Zahabu[a] and Tron Eid[b]

[a] Department of Forest Resources Assessment and Management, Sokoine University of Agriculture, P.O. Box 3013, Morogoro, Tanzania

[b] Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, 1432 Ås, Norway

[c] Forestry Training Institute, Olmotonyi, P. O. Box 943, Arusha, Tanzania

*Corresponding author: Tel +0255 752 356 999/655 408 403

Email: makerojons@yahoo.com

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Models For Prediction Of Volume Of Thicket And Associate Tree Species In Itigi Thicket Vegetation Of Tanzania

Makero, J.S.
Forestry Training Institute, Olmotonyi, P.O.Box 943, Arusha, Tanzania

Malimbwi, R.E.
Department of Forest Mensuration and Management, Sokoine University of Agriculture, P.O. Box 3013, Morogoro, Tanzania

Zahabu, E.
Department of Forest Mensuration and Management, Sokoine University of Agriculture, P.O. Box 3013, Morogoro, Tanzania

Eid, T.
Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, 1432 Ås, Norway

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ABSTRACT

The objective of this study was to develop species-specific volume models for thicket species and mixed-species volume models for associate trees in Itigi thicket. Data were collected through destructive sampling (60 thicket clumps): *Combretum celastroides* Laws and *Pseudoprosopsis fischeri* (Tab) Harms and (30 associate trees): *Canthium burtii* Bullock sensu R. B. Drumm, *Cassipourea mollis* (R. E. Fr.) Alston, *Haplocoelum foliolosum* L, *Lannea fulva* (Engl.) Engl and *Vangueria madagascariensis* J.F. Gmelin. Different nonlinear multiplicative model forms were tested, and models were selected based on coefficient of correlation (R^2) and relative root mean square error (RMSEr). Large parts of the variation in volume of thicket clumps were explained by basal area weighted mean diameter at breast height of stems in the clump, height and number of stems in the clump, i.e. *C. Celastroides* $R^2 = 0.69$ and *P. fischeri* $R^2 = 0.93$. For associate trees most variation was explained by diameter at breast height (dbh) and height (ht), i.e. $R^2 = 0.93$. Although there will be some uncertainties related to the volume estimates, for practical reasons, we recommend the selected models to be applied to the entire area where Itigi thicket extends also outside our study site, and also to those thicket and associate tree species present that were not included in the data used for modelling.

Key words: volume models, thicket, associate trees, destructive sampling

1. INTRODUCTION

Tree volume models are useful and important for forest management functions such as assessment of growing stock, timber valuation, selection of forest areas for harvests, and for growth and yield studies. Volume models have been used to estimate tree and stand volume, and have played a crucial role in forest inventories and management for more than a hundred years. Even though volume models have been studied for many years, they continue to attract forest research. One reason is that there is no single theory in volume models that can be used satisfactorily for all tree species (Clutter *et al.*, 1983, Muhairwe, 1999). Another reason is that volume models are required to be increasingly accurate and flexible in their predictions. Forest measurement needs to be improved because market requirements for timber or fuel wood have become more specific in recent years.

Many authors have reported tree volume models for different tree species and forest types. Reviews of volume models have for example been provided in Europe (Zianis *et al*., 2005), in North America (Ter-Mikaelianand Korzukhin, 1997, Jenkins *et al.*, 2004, Zhou and Hemstrom, 2010), in Australia (Grierson *et al.*, 2000, Keith *et al.*, 2000) and in sub-Saharan Africa (Henry *et al.*, 2011). Moreover, the reliability of forest volume estimates using the volume models that do exist for tropical forests is questionable because there are many species, tree sizes and geographic areas that are not covered (Henry *et al.*, 2011, Mauya *et al.*, 2014). The allometry of trees in tropical forests and the relationship between diameter at breast height and total tree height is challenging when estimating volume, therefore this variability need models calibrated for specific conditions, tree species or environmental covariates (Vieilledent *et al.*, 2012). This discrepancy, calls for a considerable amount of work on volume models in tropical forests.

Relatively small numbers of volume models have been developed in Tanzania, and most existing volume models are reported in miombo and montane forests (e.g. Malimbwi and Temu, 1984, Malimbwi *et al*., 1994, Chamshama *et al.*, 2004, Mwakalukwa *et al*., 2014, Mauya *et al.*, 2014, Masota *et al*., 2014). However, no models have been reported in Itigi thicket vegetation.

Itigi thicket (named from Itigi town in Manyoni district, Tanzania) is present in the semi-arid areas of the central parts in Tanzania. Itigi thicket extends from Manyoni district to Singida rural district and Bahi district in Dodoma region and is endemic to these areas. Itigi thicket covers an area of about 410,000ha (URT, 2008). This vegetation type is unique in its occurrence, earmarked as ecologically sensitive and comprises about 12 thicket species and 15 associated tree species (WWF, 2014). The dominant thicket species include *Pseudoprosopsis fischeri* (Tab) Harms, *Combretum celastroides* Laws and *Dicrostachys cinerea*. (L) Wight & Arn, while the dominant associate tree species in Itigi ticket vegetation include *Vangueria infausta* Burch, *Albizia petersiana* (Bolle) Oliv, *Canthium burtii* Bullock sensu R. B. Drumm and *Cassipourea mollis* (R.E. Fr.) Alston (URT, 2008). A recent sample plot inventory in the area showed that *P. fischeri* and *C. celastroides* contribute more than 50% of all stems (unpublished results).

Thicket is a dense formation of evergreen deciduous shrubs and low trees (2 – 5m), often thorny and festooned with vines (Vlok *et al.*, 2003). In eastern Africa, thickets extend from central Tanzania to the lowlands of the Somalia-Masai region all the way to Eritrea (Cowling *et al.*, 2005, Kindt *et al.*, 2011). The climate of thicket's core area is semi-arid to sub-humid (rainfall 250 – 800mm yr^{-1}) and subtropical to warm-temperate (largely frost-free). Thicket vegetation is dominated by trees and shrubs; they are very long-lived and are capable of sprouting after defoliation from herbivores, frost and fire (Cowling *et al*., 2005). Thicket supports a diverse mammal fauna, including large and medium-sized species like for example; African elephant (*Loxodonta africana*), black rhinoceros (*Diceros bicornis*), and African buffalo (*Syncerus caffer*) (Kerley *et al.*, 1995, Cowling *et al*., 2005, WWF, 2014).

The need for the development volume models that cover the actual conditions for thicket in Tanzania is therefore obvious. This is of particular importance since Tanzania recently has established a National Forest Resources Monitoring and Assessment (NAFORMA) to monitor forests and other vegetation of the entire country (URT, 2010) and such models would be useful in estimating volume in thicket. Development of such models will aid in obtaining accurate quantitative information on the amount of wood that can be produced by this vegetation for specific uses, such as fuel wood or poles for construction. The aim of this study was to develop species-specific volume models for two dominating thicket species and mixed-species volume models for associate trees in Itigi thicket vegetation in Tanzania.

2. MATERIALS AND METHODS

2.1. SITE DESCRIPTION

Data for this study were collected in Itigi thicket located in the northern part of Manyoni district, Singida region (5° 31' to 5°50'S and 34° 31' to 34° 49'E). The altitude ranges between 1,244 and 1,300m above sea level. The area has unimodal rainfall distribution with annual mean rainfall of 624mm. The minimum temperature in July is 19°C while the maximum temperature in November is 24.4°C. Geologically, the area is underlain by a basement floor of granite. The soil is silk clay loams and favours the root systems of thicket species to easily penetrate (URT, 2008).

Itigi thicket is floristically rich; it is dominated by *P. fischeri* and *C. celastroides.* Other thicket species includes*; Craibia abbreviata* subsp.burtii, *Combretum paniculatum*.Vent, *D. cinerea*, *Croton scheffleri* Pax, *Excoecaria bussei* (Pax) Pax, *Grewia forbesii* Harv. ex Mast, *Grewia similis* K.Schum, *Ochna ovata* F. Hoffm, *Rinorea angustifolia* Grey-Wilson, *Tennantia sennii* (Chiov.) Verdc. & Bridson and *Zanthoxyllum chalebium* Engl. Within Itigi thicket there are also non thicket species (associate trees) such as *Acacia tortilis*. (Forsk.) *Hayne*, *Arzeyk.*, *Baphia massaiensis* Taub.*, C. mollis, H. foliolosum*, *L. fulva* , *Senna singueana* (Delile) Lock, *Maerua triphylla* A. Rich., *V. madagascariensis*. In addition, there are also small patches of miombo woodland composed of miombo dominants such as *Brachystegia boehimii*.Benth, *Brachystegia spiciformis.* Benth, *Julbernadia globiflora* (Benth) and *Burkea africana* found in Itigi thicket (URT, 2008, WWF, 2014).

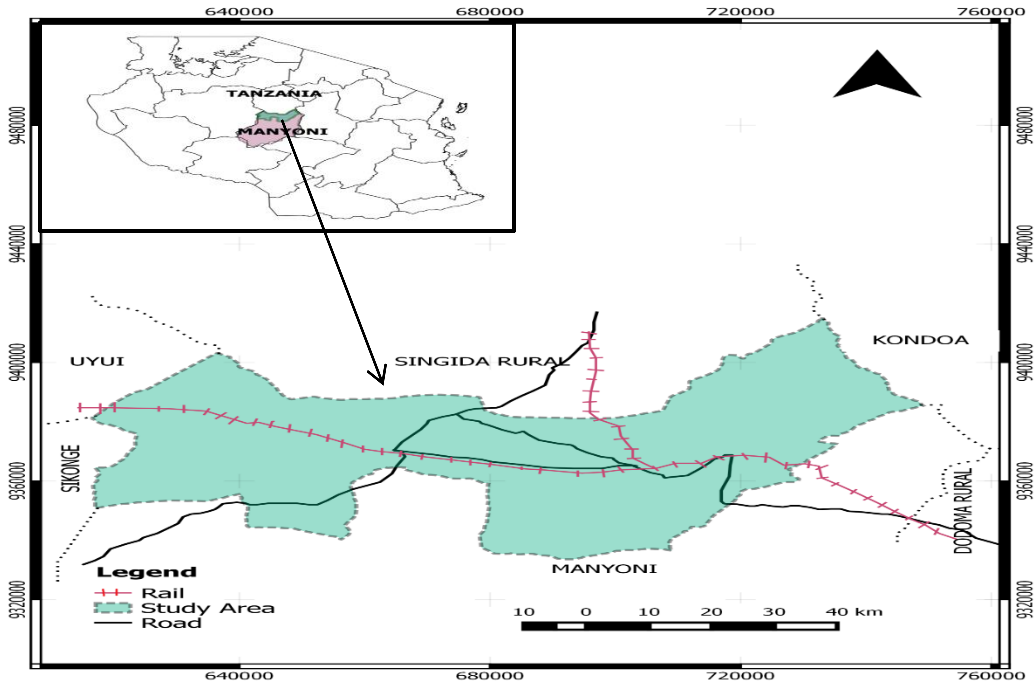


Figure 1. Location of the study area

2.2. SAMPLING THICKET CLUMPS AND ASSOCIATE TREES

Destructive sampling needs time and resource in order to get enough and accurate data for modelling. As a basis for our volume models, 60 clumps of dominant thicket species (30 clumps of *C. celastroides* and 30 clumps of *P. fischeri*) and 30 associate trees were sampled. A thicket clump here refers to a close group of stems originating from the same root sucker. An associate tree refer to a small tree (usually with a dbh below 20cm and height below 8m) found scattered in thicket stands tending to grow up when the thicket canopy cover is reduced to below 40%.

The fieldwork was carried out in two stages. The first stage involved a reconnaissance survey in order to become acquainted with the study area, delineate thicket boundaries and stratify the thicket area into either open thicket or closed thicket. Open thicket here refers to an area with thicket cover below 50% and closed thicket is an area with thicket cover above 50%. The second stage involved establishment of plots for selecting thicket clumps and associate trees. From a map displaying the thicket vegetation we randomly selected coordinates for 30 plots in the two strata open and closed thicket vegetation, respectively. The coordinates of the plot centres were located in the field using a hand held GPS. The plot size was $154m^2$ (7m radius). For each stratum (open and closed), 15 clumps of each of the two thicket species and 15 associate trees were selected.

Within each plot, two clumps of each thickets species and one associated tree were selected for destructive sampling. The two clumps of the respective thicket species were selected from those clumps with more than 5 stems that were closest to the plot centre. Among the associate tree species we selected the closest tree to the plot centre. If an associate tree was not found inside the plot, the closest tree to the plot centre outside the plot was selected.

Before felling, the thicket species was identified; the number of stems in the clump (stem count, st) was recorded and all stems measured for diameter at breast height (dbh) using a calliper. In addition, the total height of tallest stem (ht) in a clump was measured. For each clump, a basal area weighted mean dbh_w was computed in the following way;

$$dbh_w = \sqrt{\frac{\sum BA_i \times 4}{st \times 3.14159}}$$

where BA_i is basal area of the i^{th} stem in a clump.

Similarly, for each selected associate tree, the tree species was identified and measurements of dbh and ht taken. Table 1 and 2 show statistical summaries of the selected thicket clumps and the associated trees.

Table 1. Statistical summary for selected thicket clumps

Species	n	dbh_w (cm)			Height (m)			Stem count		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Combretum celastroides	30	2.4	1.5	3.2	4.5	3.5	6.5	15	6	29
Pseudoprosopis fischeri.	30	2.2	1.2	3.0	4.1	3.0	6.0	22	9	57

n= number of thicket clumps, min=minimum, max=maximum

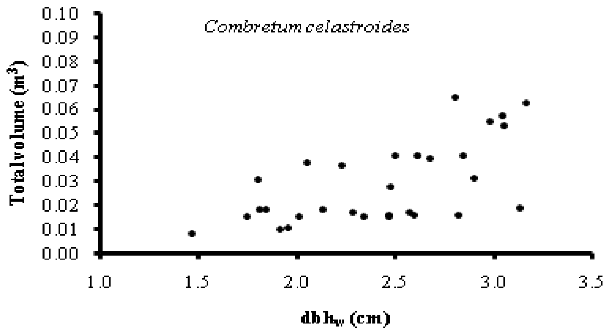
Table 2. Statistical summary for selected associate trees

Species	n	dbh (cm)			Height (m)		
		Mean	Min	Max	Mean	Min	Max
Canthium burtii	2	7.4	7.3	7.5	5.5	5.0	6.0
Cassipourea mollis	2	10.2	9.9	10.4	7.2	6.9	7.5
Haplocoelum foliolosum	8	10.7	6.1	18.0	5.9	5.0	7.0
Lannea fulva	6	10.8	10.1	11.7	5.3	5.0	6.0
Vangueria madagascariensis	12	10.0	7.0	15.2	6.2	5.0	7.2
All	30	10.0	6.1	18.0	6.0	5.0	7.5

n= number of trees, min=minimum, max=maximum

2.3 DESTRUCTIVE SAMPLING

Thicket clump volume was determined as the sum of stems volumes in a clump. The selected clumps were cut at heights of 10cm from the ground level. Felled stems were cross cut into small stems (from the stump up to the diameter of 1cm) and the remaining parts were treated as twigs. Thereafter all stems were measured separately for mid-diameter (cm) and length. The volumes of individual stems were calculated by using Huber's formula. Total volume of thicket clumps was finally obtained by summarizing the volumes of all stems. For associate trees, the selected clumps were also cut at heights of 10cm from the ground level. Felled trees were crosscut into two main components, namely stem (from the stump to the point where the first large branch protrudes the stem) and branches. Diameter cut-off between branches and twigs was 2.5cm, and no volume from twigs was included. Because our sample associate trees had dbh ranging from 6.1 to 18cm (Table 2), stems and branches were crosscut into sections with lengths generally ranging between 1-2.5m. Thereafter all stem and branch sections were measured separately for mid-diameter (cm) and length. The volumes of individual logs were calculated by using Huber's formula. Total volume of associate trees was finally obtained by summarizing the volumes of all logs. Figure 2 shows scatter plots of volume versus dbh_w for individual thicket clumps and Figure 3 shows scatter plots of volume versus dbh for associate trees.



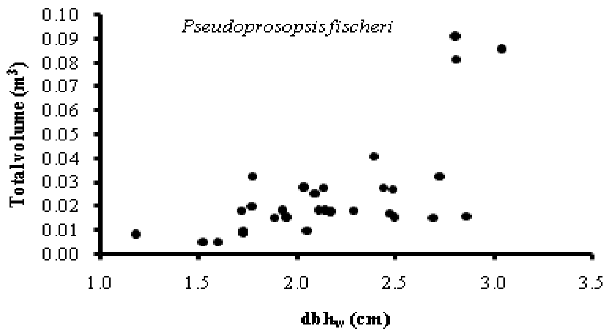


Figure 2. Scatter plots of total volume versus dbh_w for Combretum celastroides and Pseudoprosopsis fischeri

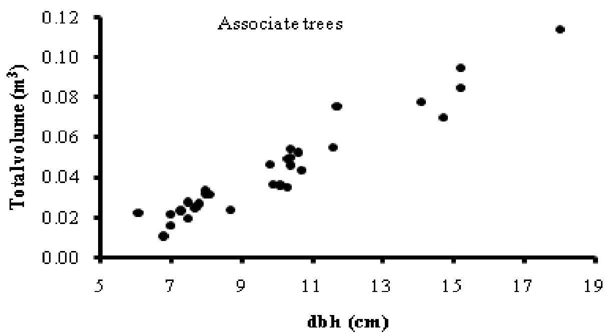


Figure 3.Scatter plots of total volume versus dbh for associate trees

2.4 MODEL DEVELOPMENT, SELECTION AND EVALUATION

For the thicket clumps, two models, i.e. model 1 with dbh_w and st as independent variables and model 2 with dbh_w, ht and st as independent variables were tested. Also for the associate trees, two models were tested, i.e. model 3 with dbh only and model 4 with dbh and ht as independent variables. The tested model forms are commonly used to develop biomass models in the literature (e.g. Mauya *et al.*, 2014).

$V = \beta_0 \times dbh^{\beta 1} \times st^{\beta 2}$ (model 1)

$V = \beta_0 \times dbh^{\beta 1} \times ht^{\beta 2} \times st^{\beta 3}$ (model 2)

$V = \beta_0 + \beta_1 \times dbh^2$ (model 3)

$V = \beta_0 \times dbh^2 \times ht$ (model 4)

where V is total volume of thicket clumps or associate trees, and β_0, β_1, β_2 and β_3 are model parameters.

The PROC NLN procedure in SAS software (SAS_ Institute Inc., 2004) was used to estimate the model parameters (β_0, β_1, β_2, and β_3). The procedure produces the least squares estimates of the parameters of a nonlinear model through an iteration process.

The coefficient of correlation (R^2) and relative Root Mean Squared Error (RMSEr) were reported for all models, and used for selection among alternative models. Details in calculating RMSEr were;

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(v_i - \hat{v}_i)^2}{n}} \qquad RMSEr = \frac{RMSE}{\bar{v}_x} x100$$

where n is the number of trees, v_i is the observed volume of tree i, $\hat{v}_i$ is the predicted volume, and $\bar{v}_x$ is the mean observed volume.

The selected models were further evaluated by means of relative Mean Prediction Error (MPEr) and the relative standard deviation of residuals (STDr), which were calculated as;

$$MPE = \sum_{i=1}^{n} \frac{(v_i - \hat{v}_i)}{n} \qquad MPEr = \frac{MPE}{\bar{v}_x} x100$$

$$STD = \sqrt{\sum_{i=1}^{n} \frac{(v_i - \hat{v}_i)^2}{n-1}} \qquad STDr = \left(\frac{STD}{\bar{v}_x}\right) x100$$

Paired *t*-tests were also done to determine whether MPEr were significantly different from zero.

Determination of dbh_w (see Table 1) requires the diameter of all stems in a clump to be measured in field. Since this is time consuming, an alternative could be to sample only a few trees in the clump for dbh_w determination. We therefore tested a procedure where the smallest, the medium and the largest stem regarding diameter in the clump were selected and measured for dbh. From these three trees, mean diameter weighted by basal area were calculated and compared with the corresponding diameter from all stems. Student t-test was done to determine whether the differences were significantly different from zero.

3. RESULTS

Parameter estimates and performance criteria for the two thicket species volume models are summarized in Table 3. For *C. celastroides*, R^2 varied from 0.64 to 0.69. Based on the model selection criteria, model 2 was judged best by R^2 (0.69) and RMSEr (31.8%). For *P. fischeri*, R^2 varied from 0.92 to 0.93. Therefore, model 2 was also judged best by RMSEr (23.3%) and R^2 (0.93). Table 3 also summarizes parameter estimates and performance criteria for associate trees. Based on the model selection criteria, model 4 was judged best by RMSEr (14.3%) and R^2 (0.93).

The selected models for thicket clumps and associate trees were further evaluated over dbh-classes by means of relative MPEr (Table 4). Overall, for all observations, no MPEr were significantly different from zero for any species. However, for *C. celastroides*, the models significantly over-predicted the volume for clumps in the medium dbh-class. For *P. fischeri*, no MPE different from zero were seen for any dbh class. Similarly, no MPEr were different from zero were observed for any dbh-class.

Table 3. Estimated parameters, R^2 and RMSEr for volume models of thicket clumps and associate trees

Species	n	Mean observed volume (m^3)	Model	β_0	β_1	β_2	β_3	R^2	RMSEr %
Combretum celastroides	30	0.0291	1	0.000299	2.961014	0.691212		0.64	34.6
	30	0.0291	2	0.000230	2.461515	0.908853	0.453408	0.69	31.8
Pseudoprosopis fischeri	30	0.0256	1	0.002630	2.292486	0.876201		0.92	24.0
	30	0.0256	2	0.000166	2.217730	0.546812	0.790309	0.93	23.3
Associate trees	30	0.0445	3	0.006060	0.00353			0.92	15.8
	30	0.0445	4	0.000420	1.50092	0.64185		0.93	14.3

*Parameter estimate not significant ($p > 0.05$), selected models in bold

Table 4. Evaluation of selected volume models over diameter classes for thicket clumps and associate trees

Species	Dbh-class[1]	n	Model	Total volume (m^3)		MPEr %	p-value for MPE	STD m^3	STDr %
				Observed	Predicted				
Combretum celastroides	-2.1	10	2	0.0185	0.0144	7.4	0.2293	0.0100	54.2
	2.2-2.6	10	2	0.0245	0.0290	-6.1	0.0291	0.0055	22.3
	2.7-	10	2	0.0442	0.0428	1.1	0.6784	0.0105	23.8
	All	30	2	0.0291	0.0209	1.2	0.8440	0.0094	32.3
Pseudoprosopis fischeri	-1.9	11	2	0.0142	0.0126	4.0	0.3109	0.0048	33.8
	2.0-2.4	10	2	0.0232	0.0229	0.3	0.9261	0.0081	34.8
	2.5-	9	2	0.0423	0.0441	-1.2	0.3242	0.0050	11.9
	All	30	2	0.0256	0.0255	0.5	0.9155	0.0061	23.3
Associate trees	-8	11	4	0.0235	0.0241	-0.93	0.7176	0.0053	22.6
	8.1-10.4	10	4	0.0409	0.0404	0.40	0.8228	0.0067	16.3
	>10.4	9	4	0.0743	0.0743	-0.01	0.9960	0.0081	10.9
	All	30	4	0.0445	0.0446	-0.13	0.9600	0.0065	14.5

[1] Forthicket clumps, dbh class refers to dbh_w

The behaviour of the selected *C. celastroides* and *P. fischeri* models over dbh_w with different assumptions for heights (ht) and stem counts (st) are presented in Figures 4 and 5.

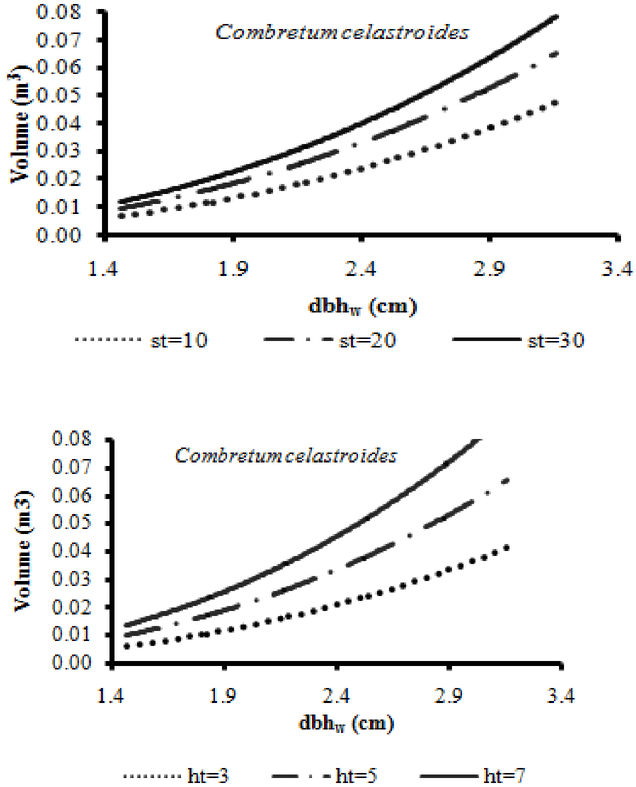
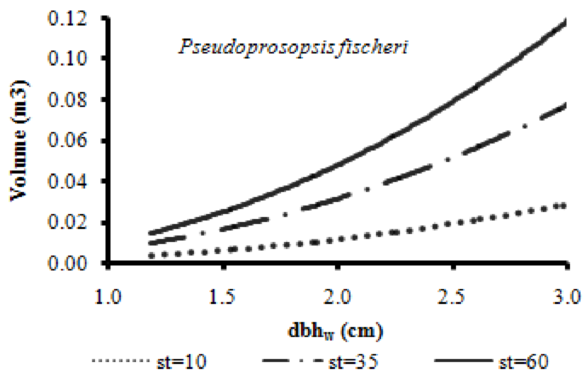


Figure 4. Display of predicted total volume over dbh_w with varying stem counts (upper panel, height =5 m) and varying heights (lower panel, stem count = 20 cm) for the selected Combretum celastroides models



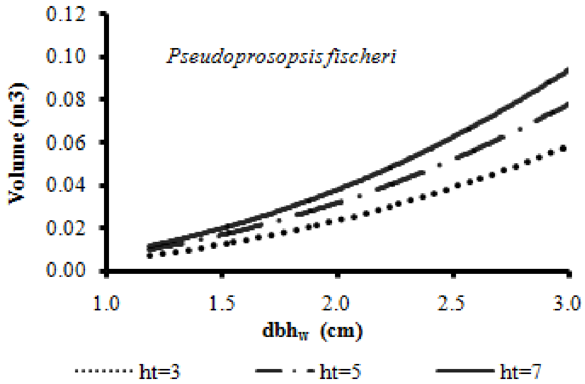


Figure 5. Display of predicted total volume over dbh_w with varying stem counts (upper panel, height = 5 m) and varying heights (lower panel, stem count = 35 for the selected Pseudoprosopsis fischeri models

The results regarding the differences when comparing dbh_w from all stems with dbh_w from the three selected stems (smallest, medium and largest) are presented in Table 5. For both species, the dbh_w were significantly overestimated when using the three selected stems, i.e. by 14.0% for *C. Celastroides* and by 5.5% for *P. fischeri.*

Table 5. Differences in dbh_w from all stems and from three selected stems

Species	n	Basal area weighed mean dbh based on all stems(dbh_w)	Basal area weighed mean dbh based on three stems(dbh_w)			
			Mean	Diff.	Diff (%)	p-value
Combretum celastroides	30	2.43	2.77	0.34	14.0	0.0000
Pseudoprosopis fischeri	30	2.17	2.29	0.12	5.5	0.0006

4. DISCUSSION

The volume models presented in this study are the first ones developed for thicket in Tanzania. Two dominant thicket species (i.e. *C. celastroides* and *P. fischeri*) were focused because of the limited resources to cover all thicket species present in Itigi thicket. The selection of thicket clumps for modelling was based on randomly distributed sample plots within the study area to secure the clumps to be as representative as possible. Also within each plot, the thicket clumps were selected randomly. Thus, clumps with wide ranges regarding different sizes were covered, i.e. dbh_w ranged from 1.2cm to 3.2cm, ht from 3m to 6.5m and st from 6 to 57 (Table 1). Use of modelling data with appropriate numbers of both small and large clumps is important in order to avoid extrapolation and the uncertainty related to this as much as possible.

The R^2 and RMSEr of the thicket models clumps varied between the species, i.e. *C. celastroides*: R^2 0.64 - 0.69, RMSEr 31.8% - 34.6% and *P. fischeri*: R^2 0.92 - 0.93, RMSEr 23.3% - 24.0% (Table 3). There were improvements in the performance criteria (R^2 and RMSEr) when ht was included as an independent variable (see Table 3). The improvements were moderate, however, which conform with several previous studies (e.g. Malimbwi *et al.*, 1994, Abbot *et al.*, 1997, Guendehou *et al.*, 2012). Due to the morphological differences between the two thicket species, the fit of the *C. Celastroides* volume models was not as good as the fit of the *P. fischeri* volume models.

The comparison of the two methods for determination of dbh_w for the clumps revealed significant overestimation when basing this on the three selected trees, i.e. by 14.0% for *C. celastroides* and by 5.5%for *P. fischeri* (Table 5). If such values are applied in the models, they will lead to large overestimations of volume. It is therefore recommended that all stems are measured for diameter in practical inventories in order to avoid large biases.

The species-specific thicket clump models developed may generally be applied inside the study site (Manyoni). The models may also be applied outside this site where Itigi thicket extends (i.e. Singida rural district and Bahi district in Dodoma region) because growing conditions here are very similar. Although Itigi thicket comprise of more than 10 different species, a recent sample plot inventory in the area showed that the two selected species contribute to more than 50% of the total stem density (unpublished results). For practical reason when estimating volume for larger areas we therefore recommend the models to be applied also to remaining thickets species with similar morphology. The uncertainty in volume estimates will of course increase by doing this, but this is the only option since models do not exist for the remaining species.

The selection of associate trees for modelling was also based on randomly distributed sample plots to secure the associate trees to be as representative as possible. Within each plot, an associate tree was also selected randomly. Thus, associate trees with wide ranges regarding different sizes were covered, i.e. dbh ranged from 6.1cm to 18cm (see Table 2). Five different tree species (*C. burtii, C. mollis, H. foliolosum, L. fulva* and *V. madagascariensis*), out of a total of 15 tree species, were selected. Since the trees were selected randomly, the five species will comprise a large part of the volume in the area, and as such, the uncertainty related to the relatively few species included in the mixed-species models will be relatively low when applying them also to the remaining species.

The number of sampled associate trees was relatively small (30) compared to that used to develop tree volume models for miombo woodlands in Tanzania (see Mauya *et al.,* 2014, Mwakalukwa *et al*., 2014). However, the number of sampled associate trees was relatively high compared sample trees used to develop previous models in miombo woodlands (Malimbwi *et al.,* 1994, Chamshama *et al*., 2004).

There were improvements in the performance criteria (R^2 and RMSEr) for the associate trees when ht was included as an independent variable (see Table 3). The improvements were moderate, however, which also conform with several previous studies (e.g. Malimbwi *et al*., 1994, Abbot *et al.,* 1997, Guendehou *et al.,* 2012). Generally for the associate trees, large parts of the variations in volume were explained by dbh and ht. Therefore the obvious choice was for this model (Table 3). The application recommendation for associate tree model is similar to those of the thicket clumps; for the study site, and outside where the Itigi thicket vegetation extends.

5. CONCLUSION AND RECOMMENDATION

The developed species-specific models for thicket and mixed-species models for associate trees were based on a wide-range of sizes and well-documented sets of data comprising dominant thicket and associate tree species. The model fitting showed that large parts of the variation in volume of thicket were explained by basal area weighed mean diameter at breast height, height and number of stems in the thicket clumps while for associate trees most variation was explained by diameter at breast height and height. Although there will be some uncertainties related to volume estimates for large areas, for practical reasons, we recommend the selected models to be applied to the entire area where Itigi thicket extends outside our study site, and also to those thicket and associate tree species present that were not included in the data used for modelling.

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APPENDIX 1

Sample clumps and associate trees used to develop total volume models and their respective names and sizes.

A: Thicket clump

Combretum celastroides				Pseudoprosopsis fischeri			
dbh_w (cm)	ht (m)	st	v (m^3)	dbh_w (cm)	ht (m)	st	v (m^3)
1.5	4.5	15	0.008	1.2	4.0	20	0.008
1.7	4.4	12	0.016	1.5	3.5	18	0.005
1.8	4.0	9	0.031	1.6	3.0	12	0.005
1.8	4.5	29	0.019	1.7	4.0	36	0.018

1.8	5.0	27	0.019	1.7	4.0	23	0.010
1.9	4.5	8	0.010	1.7	4.0	13	0.008
2.0	4.4	14	0.011	1.8	4.0	25	0.020
2.0	4.4	11	0.015	1.8	4.5	31	0.033
2.1	3.9	13	0.038	1.9	4.5	18	0.015
2.1	4.0	25	0.018	1.9	3.5	16	0.019
2.2	4.8	29	0.037	1.9	3.0	16	0.015
2.3	4.0	12	0.017	2.0	4.5	20	0.028
2.3	4.4	8	0.016	2.1	4.0	22	0.010
2.5	3.5	13	0.016	2.1	5.5	38	0.025
2.5	4.3	10	0.016	2.1	3.0	18	0.019
2.5	4.4	21	0.028	2.1	4.5	19	0.027
2.5	6.5	25	0.041	2.1	3.0	17	0.019
2.6	4.3	10	0.017	2.2	4.5	16	0.018
2.6	3.5	20	0.016	2.3	4.0	21	0.018
2.6	5.2	17	0.041	2.4	6.0	17	0.041
2.7	5.0	19	0.040	2.4	3.5	22	0.028
2.8	4.5	17	0.065	2.5	4.5	13	0.017
2.8	4.3	8	0.016	2.5	4.0	19	0.027
2.8	4.2	17	0.041	2.5	4.0	13	0.015
2.9	4.5	10	0.032	2.7	4.0	10	0.015
3.0	5.0	12	0.055	2.7	4.0	21	0.033
3.0	5.6	18	0.057	2.8	5.0	57	0.091
3.1	4.9	14	0.054	2.8	4.5	42	0.081
3.1	3.5	6	0.019	2.9	4.0	9	0.016
3.2	5.2	13	0.063	3.0	5.0	38	0.086

B: Associate trees

Species	dbh (cm)	ht (m)	v (m^3)
Haplocoelum inopleum	6.1	5.0	0.022
Haplocoelum inopleum	6.8	5.0	0.011
Haplocoelum inopleum	7.0	5.2	0.021
Vangueria madagascariensis	7.0	5.0	0.016
Canthium burtii	7.3	5.0	0.023
Canthium burtii	7.5	6.0	0.019
Haplocoelum inopleum	7.5	5.0	0.028
Vangueria madagascariensis	7.7	5.0	0.025
Vangueria madagascariensis	7.8	5.3	0.027
Vangueria madagascariensis	8.0	5.5	0.034
Vangueria madagascariensis	8.0	5.0	0.032
Vangueria madagascariensis	8.1	5.5	0.031
Vangueria madagascariensis	8.7	6.0	0.024
Vangueria madagascariencies	9.8	6.0	0.046
Cassipourea mollis	9.9	6.0	0.037
Lannea fulva	10.1	5.0	0.036
Haplocoelum inopleum	10.3	6.0	0.035
Haplocoelum inopleum	10.3	5.1	0.049
Lannea fulva	10.4	6.0	0.046
Cassipourea mollis	10.4	6.0	0.050
Lannea fulva	10.4	7.0	0.055
Lannea fulva	10.6	6.7	0.053
Vangueria madagascariencies	10.7	7.0	0.044
Lannea fulva	11.6	6.9	0.055
Lannea fulva	11.7	7.2	0.076
Vangueria madagascariensis	14.1	7.0	0.078
Haplocoelum inopleum	14.7	7.0	0.070
Vangueria madagascariensis	15.2	7.2	0.085
Vangueria madagascariensis	15.2	7.5	0.095
Haplocoelum inopleum	18.0	7.0	0.114

PAPER FOUR

Estimation volume and biomass of thicket and associate tree species in Itigi thicket, Tanzania

Joseph Sitima Makero [1,2], Eliakimu Zahabu [1] and Rogers Ernest Malimbwi [1]

1. Department of Forest Resources Assessment and Management, Sokoine University of Agriculture, P.O. Box 3013, Morogoro, Tanzania

2. Forestry Training Forestry, Olmotonyi, P.O. Box 943 Arusha, Tanzania

*Corresponding author: Tel +0255 752 356 999/655 408 403

Email: makerojons@yahoo.com

Due for submission

Estimation of volume and biomass of thicket and tree species in Itigi thicket, Tanzania

J.S. MAKERO, R.E. MALIMBWI and E. ZAHABU

Forestry Training Institute, Olmotonyi, P.O. Box 943, Arusha, Tanzania, Sokoine University of Agriculture, P.O. Box 3013, Morogoro, Tanzania
Email: makerojons@yahoo.com, remalimbwi@yahoo.com and zahabue@yahoo.com

SUMMARY
The study was conducted to assess volume and biomass of thicket and tree species in Itigi thicket. A total of 86 circular plots with radius of 7 m were used to collect data on thicket and tree species. Volume and biomass for individual thicket and tree species were estimated by using models developed for Itigi thicket. A total of 28 wood species belonging to 16 families were identified. Volume and biomass (AGB/BGB) in Itigi thicket is estimated to 8.1±1.0 m^3 and 8.7±1.2 t/4.1±0.6 t per ha respectively. Although Itigi thicket has lower composition of wood species, volume and biomass, the vegetation has larger number of stems per ha than miombo woodland, thus needs to be managed sustainably.

Key words: biomass, volume, thicket, Itigi thicket

INTRODUCTION
Woodlands in Africa are diverse vegetation formations that include woodland proper, bushland, thicket and in some cases, wooded grassland (CIFOR, 2010). Thicket is a dense formation of evergreen deciduous shrubs and low trees (2 - 5m), often thorny and festooned with vines (Vlok *et al.*, 2003). In eastern Africa, thicket extends from central Tanzania to the lowlands of the Somalia-Masai region to Eritrea (Kindt *et al.*, 2011). Thicket is dominated by shrubs and trees, that are very long-lived and are capable of sprouting after defoliation by herbivores and fire (Cowling *et al*., 2005). Thicket vegetation supports a diverse of mammals, including large and medium-sized species like African elephant (*Loxodonta africana*), black rhinoceros (*Diceros bicornis*), and African buffalo (*Syncerus caffer*) (WWF, 2014). Thicket also offers both direct tangible benefits to man (e.g. fuel wood, construction and craft materials, medicines, food) and fodder for animals. Indirect benefits including environmental services such as carbon sequestration, biodiversity and soil and water conservation (WWF, 2014).

In Tanzania, thicket extends from Manyoni District to Singida rural District and Bahi District in Dodoma region and is endemic to these areas. This vegetation is popular known as Itigi thicket, (named from Itigi town in Manyoni district, Tanzania). Itigi thicket covers an area of about 410,000 ha (URT, 2008). This vegetation type is unique in its occurrence, earmarked as ecologically sensitive for conservation (WWF, 2014). Itigi thicket contains at least 100 wood species, which are mostly spineless, multi-branched shrubs of 3 – 5 m in height, characterized by *Baphia burttii*, *B. massaiensis*, *Bussea massaiensis*, *Burttia prunoides*, *Combretum celastroides*, *Grewia burttii*, *Pseudoprosopsis fischeri*, and *Tapiphyllum floribundum*. *Albizia petersiana*, *Craibia brevicaudata subsp. burtii*, and *Bussea massaiensis* occasionally emerge from the lower canopy (White 1983) to form an open, upper canopy of 6 - 12 m height.

Estimation of volume and biomass are the most persistent uncertainties in understanding and monitoring the carbon cycle. This is especially true in tropical forest because of its complicated stand structure and species heterogeneity (Lu, 2006). Volume and biomass provide an estimate of carbon stock present in the forest vegetation. It is estimated that up to 50 % of biomass is carbon. Therefore, estimating the biomass of the forests is basically important in order to understand their carbon storage potential (Munishi *et al.*, 2004).

Despite the rapid conversions of tropical vegetation (i.e. forests, woodlands, bushland, thicket) to other land uses, tropical vegetations play a crucial role as one of the carbon sinks for atmospheric carbon dioxide. As Tanzania likes to have high potential for carbon storage and mitigating CO_2 emissions, reliable estimates for volume and biomass potential for all vegetation is inevitable. The potential of Tanzania's vegetation including Itigi thicket to sequester or store carbon is a key to understanding whether the corrective measures taken in land use changes and forest management are likely to create net carbon sources or sinks.

However, there is no study reported on volume and biomass of thicket and tree species in Itigi thicket. Many studies reported volume and biomass of tree species in other vegetation types, for example Chamshama *et al.* (2004); Zahabu (2008); Mwakalukwa *et al.* (2014), reported in miombo woodland, Munishi *et al.* (2010) reported in montane forests and NAFORMA reported in miombo woodland, montaine forests, mangrove forests and trees outside the forest. In regard to significance of Itigi thicket to sequester carbon, further investigation on volume and biomass stocks of thicket and trees were prospective.

This paper presents an attempt to assess volume and biomass of thicket and tree species. Specifically, the study aimed at assessing species composition, volume, above- and belowground biomass of thicket and tree species. The following question was used to guide the research: (1) Do volume and biomass for thicket relates with that of trees?

MATERIALS AND METHODS

Site description

Data for this study were collected in Itigi thicket located in the northern part of Manyoni district, Singida region (5° 31' to 6°00'S and 34° 31' to 35° 00'E). The altitude of the area ranges between 1,244 and 1,300 m above sea level. The area has annual mean rainfall of 624 mm. The minimum temperature in July is 19°C while the maximum temperature in November is 24.4°C. Geologically, the area is underlain by a basement floor of granite. The soil is silk clay loams and favours the root systems of thicket species to easily penetrate (URT, 2008).

Itigi thicket is dominated by *P. fischeri* and *C. celastroides.* Other thicket species include *Craibia abbreviata* subsp.burtii, *Combretum paniculatum*.Vent, *D. cinerea*, *Croton scheffleri* Pax, *Excoecaria bussei* (Pax) Pax, *Grewia forbesii* Harv. ex Mast, *Grewia similis* K.Schum, *Ochna ovata* F. Hoffm, *Rinorea angustifolia* Grey-Wilson, *Tennantia sennii* (Chiov.) Verdc. & Bridson, and *Zanthoxyllum chalebium* Engl. Within Itigi thicket there are also non thicket species (emergent trees) such as *Acacia tortilis*. (Forsk.) *Hayne, Arzeyk.*, *Baphia massaiensis* Taub., *C. mollis, H. foliolosum, L. fulva* , *Senna singueana* (Delile) Lock, *Maerua triphylla* A. Rich., *V. madagascariensis*. In addition, there are also small patches of miombo woodland composed of miombo dominants such as *Brachystegia boehimii.*Benth, *Brachystegia spiciformis.*Benth, *Julbernadia globiflora* (Benth) and *Burkea africana* found in Itigi thicket (URT, 2008,WWF, 2014).

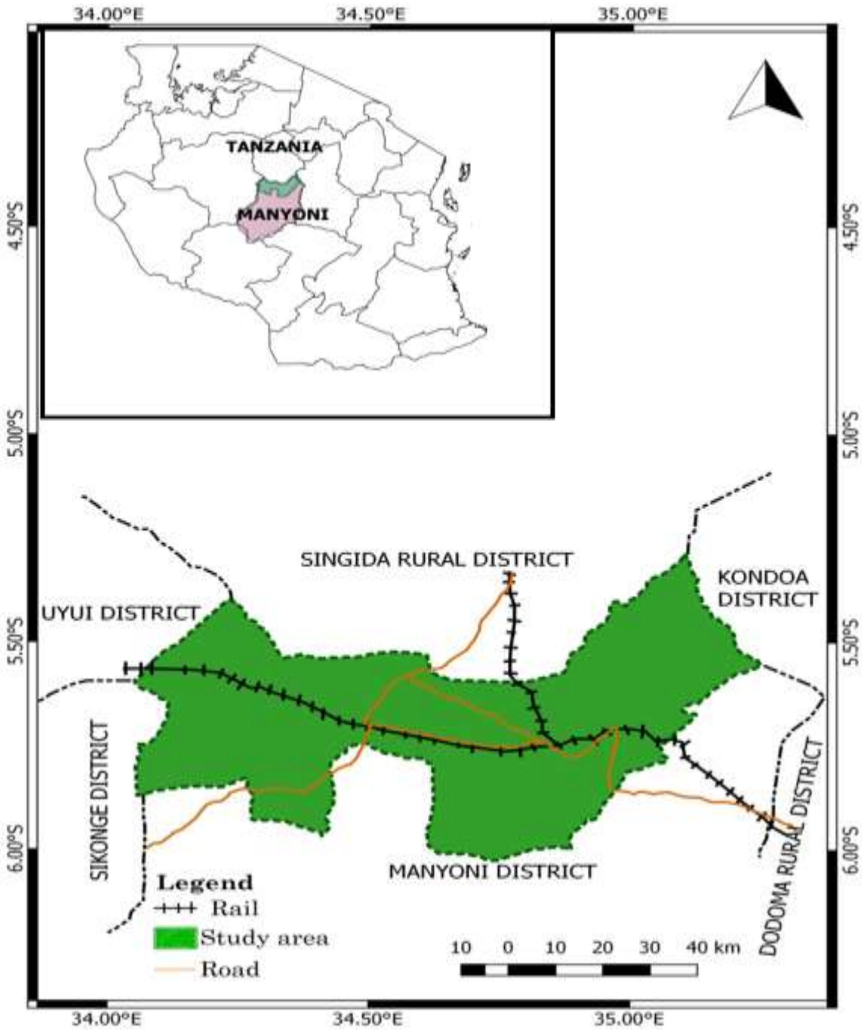


FIGURE 1**:** *Location of the study site*

Data Collection

The total number of sample plots was 86 with a sampling intensity of 0.0005 %. Reasons behind for employing this number of plots include limited finances and time constraint. According to Malimbwi and Mugasha (2002) and Malimbwi *et al.* (2005), financial and time constraints and purpose of the forest inventory may dictate the sampling unit to be as low as 0.01 %.

The fieldwork was carried out in two stages. The first stage involved a reconnaissance survey in order to become acquainted with the study area, delineate thicket boundaries and stratify the thicket area into either open thicket or closed thicket. Open thicket here refers to an area with thicket cover of below 50 % and closed thicket is an area with thicket cover of above 50 %. The second stage involved establishment of plots for measuring thicket and tree species. From a map displaying the thicket vegetation, coordinates were randomly selected for 43 plots in the two strata of open and closed thicket vegetation respectively. The coordinates of the plot centres were located in the field using a hand held GPS. The plot size was 154 m^2 (7 m radius).

Within a plot, the names of all thicket clumps were identified and selected for measurements. For each thicket clump, the number of stems (stem count, st) was recorded and three stems (smallest, medium and largest) measured for dbh using a calliper. In addition, the total height (ht) of the tallest stem in a clump was measured. For each clump, a basal area weighted mean dbh (dbh_w) was computed as follows:

$$dbh_w = \sqrt{\frac{\sum BA_i \times 4}{st \times 3.14159}}$$

where BA_i is basal area of the i^{th} stem in a clump.

Similarly, within a plot, all trees were selected, their names identified and dbh and ht measured. Table 1 shows summary statistics of sample thicket clumps and trees used for volume and biomass estimation.

TABLE 1: Summary statistics of sample thicket clumps and trees used for volume and biomass estimation

Species	n[1]	Dbh[2] (cm)			Height (m)			Stem count		
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Thicket	682	2.6	0.2	5.0	4.3	1.5	7.0	42	1	83
Tree	40	10.8	3.2	18.4	5.3	2.5	8.0			

[1] For thicket clumps, n refers clumps and for tree refers stems
[2.] For thicket clumps, dbh refers to dbh_w

Data analysis
Species coding

Each species was coded with numbers to ease the analysis work in computer spreadsheet programs i.e. Ms Excel. The identified species were 28 (Appendix 1).

Diameter classes

For easy of presentation thicket stand, parameters were separated into five diameter classes for thicket species and into four diameter classes for tree species (Table 2).

TABLE 2**:** Diameter classes for thicket and tree species

Thicket species		**Tree species**	
Diameter class	[1]Dbh range (cm)	Diameter class	Dbh range (cm)
1	0-1	1	0-5.0
2	1.1-2.0	2	5.1-10.0
3	2.1-3.0	3	10.1-15.0
4	3.1-4.0	4	>15.0
5	>4.0		

[1] For thicket clumps, dbh refers basal area weighted mean dbh

Volume

Volume of individual thicket clump was calculated using models developed by Makero *et al.* (2016a). The models are:

$$V_C = 0.0002 \times dbh^{2.4615} \times ht^{0.9089} \times st^{0.4534}$$

$$V_P = 0.0002 \times dbh^{2.2177} \times ht^{0.5468} \times st^{0.7903}$$

Where, V_C = volume of *Combretum celastroides*,
V_P = volume of *Pseudoprosopsis fischeri*,
dbh = basal area weighted mean dbh,
ht = total height of clump,
st = stem count.

Volume of individual tree was calculated using models developed by Makero *et al.* (2016a). The models are:

$$V_T = 0.0004 \times dbh^{1.5009} \times ht^{0.6419}$$

Where, V_T = volume of a tree,
dbh = diameter at breast height of a tree,
ht = total height of a tree.

Biomass

Above- and belowground biomass for individual thicket clump were calculated using models developed by Makero *et al.* (2016b). The models are:

$$AGB_C = 0.7269 \times dbh^{2.6710} \times ht^{0.5737} \times st^{0.2039}$$

$$AGB_P = 0.4276 \times dbh^{2.4053} \times st^{0.5290}$$

$$BGB_C = 0.1006 \times dbh^{4.0062} \times st^{0.3499}$$

$$BGB_P = 0.1442 \times dbh^{4.1534} \times st^{0.4117}$$

Where, AGB_C = aboveground biomass of *Combretum celastroides*,
ABG_P = aboveground biomass of *Pseudoprosopsis fischeri*,
BGB_C = belowground biomass of *Combretum celastroides*,
BGB_P = belowground biomass of *Pseudoprosopsis fischeri*,
dbh = basal area weighted mean dbh,
ht = total height of clump,
st = stem count.

Above- and belowground biomass for trees were calculated using models developed by Makero *et al.* (2016b). The models are:

$$AGB_T = 1.2013 \times dbh^{1.5076}$$

$$BGB_T = 1.3803 \times dbh^{1.1671}$$

Where, AGB_T = aboveground biomass of a tree,
BGB_T = belowground biomass of a tree,
Dbh = diameter at breast height,
Ht = total height of tree.

In order to comply with species-specific models, thicket species were classified by their families and observed stem structures. Then, two groups were formed (group of species related to *Combretum celastroides* and group of species related to *Pseudoprosopis fischeri*). For each group, the respective species-specific models were applied to quantify volume and biomass of individual thicket clump. It was assumed that, the two thicket species (i.e. *Combretum celastroides* and *Pseudoprosopis fischeri*) represent average population characteristics of thicket species in Itigi thicket. In addition, student t-test was done to test if volume and biomass for thicket and tree were significantly different.

RESULTS

Thicket and tree species composition

The total number of thicket and tree species observed in Itigi thicket is 28 including 13 of thicket species and 15 of tree species. Figure 2 shows the woody species which contribute high in term abundance, volume and biomass. The wood species include; *Pseudoprosopsis fischeri*, *Combretum celastroides*, *Dicrostachys cinerea* and *Baphia massaiensis*. These thicket species with exception of *Dicrostachys cinerea* and *Baphia massaiensis* are endemic to Itigi thicket.

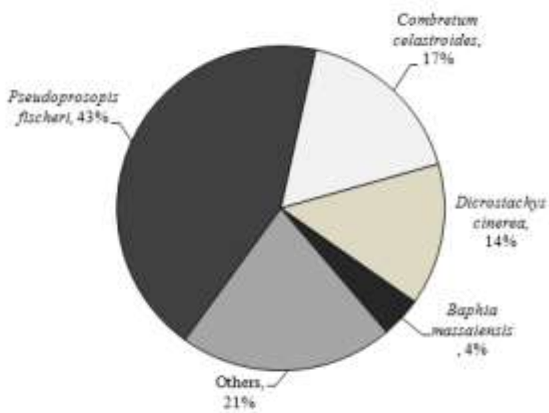


FIGURE 2: Major woody species in Itigi thicket

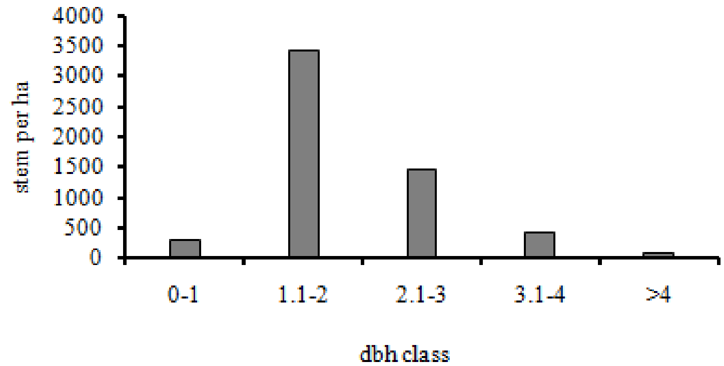
Stand parameters

Table 3 and Appendix 2 show the statistics of stand parameters for Itigi thicket. The results show that, the volume estimates per ha of Itigi thicket is 8.1±1.0m^3. When using t test, comparisons of volume with thicket and tree species showed that the volume were statistically significant different (p = 0.0000). The AGB estimates per ha of Itigi thicket is 8.7±1.2 t and BGB estimates per ha is 4.1±0.6 t (Table 3 and Appendix 2). Biomass for thicket and tree species were statistically significant different (p = 0.0000). The results also show that, basal area of Itigi thicket is 2.2 m^2/ha.

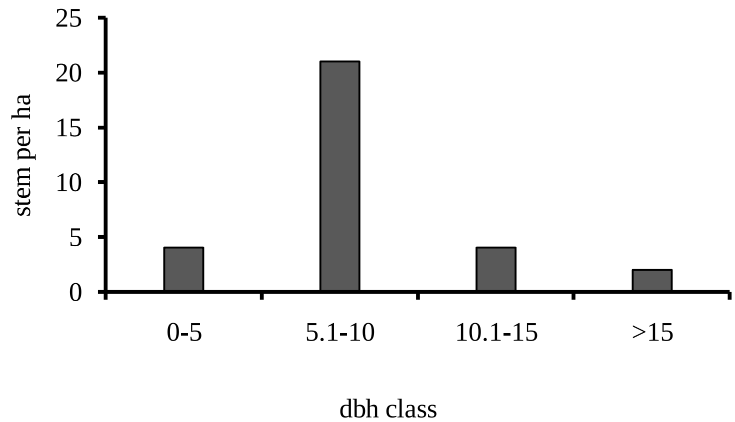
TABLE 3: Statistics of stand parameters for Itigi thicket

Statistical parameters	Form	Stems per ha	Basal area (G, m^2/ha)	Aboveground biomass (AGB, t/ha)	Belowground biomass (BGB, t/ha)	Volume (V, m^3/ha)
Mean	Thicket	5735	2.0	7.8	3.6	7.2
	Tree	30	0.2	0.9	0.5	0.9
	all	5765	2.2	8.7	4.0	8.1
Standard Error	all	646	0.3	1.2	0.6	1.0
Standard Deviation	all	5992	2.5	10.7	5.3	9.1
Number of plots		86	86	86	86	86

The distribution of stand parameters by diameter classes and species is shown in Appendix 3 (a) and (b). Figure 3 (a) and (b) shows the distribution of number of stems per ha by diameter classes. This distribution suggests that there are many small diameter thicket species between >1 and <2 cm diameter classes and also there are many small diameter tree species between >5.1 and <10.1 diameter classes.



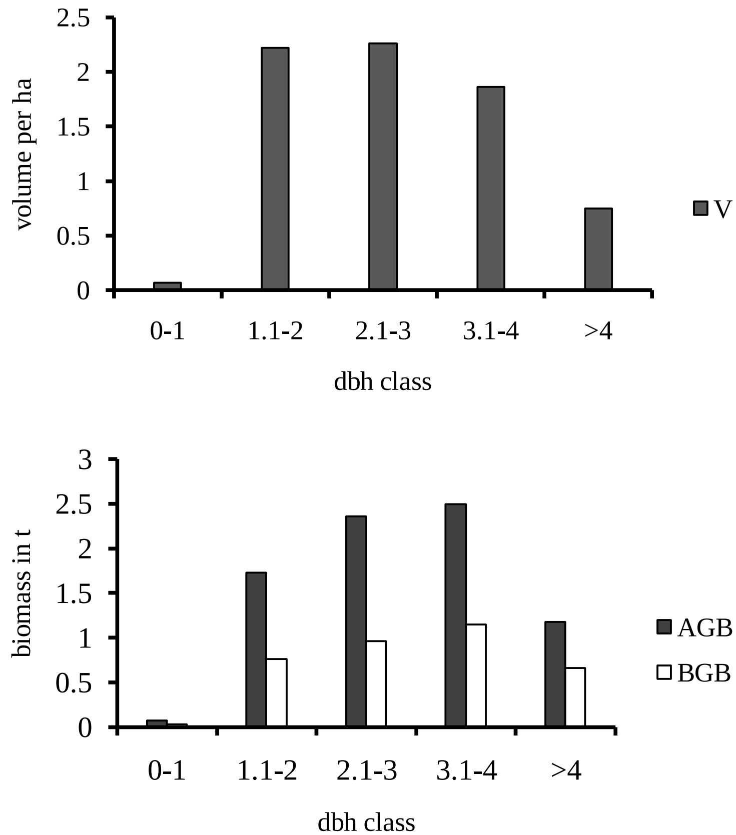
(a)



(b)

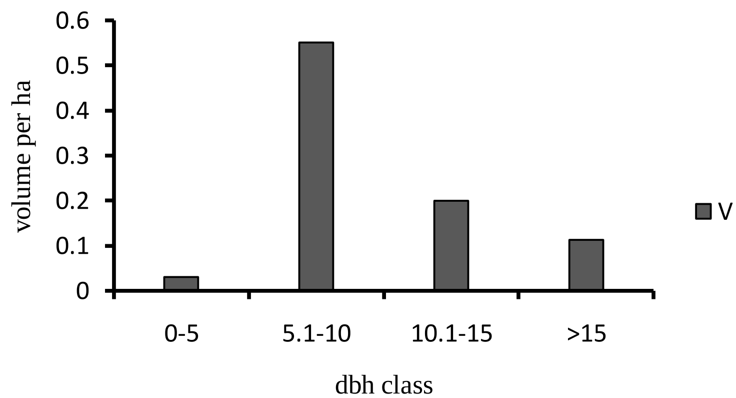
FIGURE 3: Distribution of number of stems per ha by diameter classes in Itigi thicket (a) thicket species (b) tree species

Figure 4 (a) and (b) shows the distribution of volume and biomass per ha by diameter classes. This distribution shows that most volume is in the diameter class 2.1 - 3 for thicket species and diameter class 5.1 - 10.0 for tree species. The figure also shows that most biomass is in the diameter class 3.1 - 4 for thicket species and the diameter class 5.1 - 10.0 for tree species.

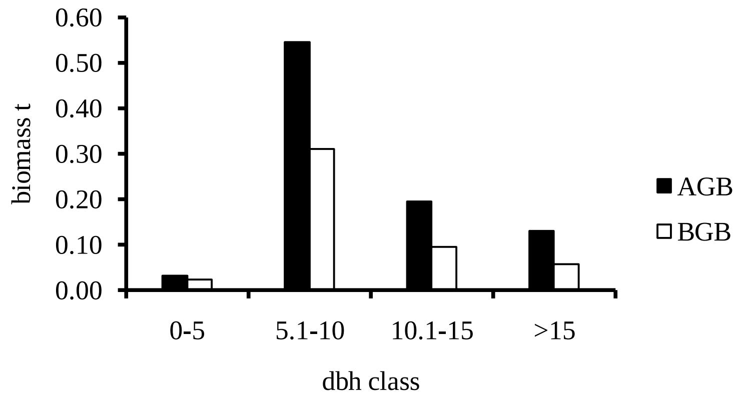


volume per ha
2.5
2
1.5
1
0.5
0
0-1
1.1-2
2.1-3
3.1-4
>4
dbh class
V
biomass in t
3
2.5
2
1.5
1
0.5
0
0-1
1.1-2
2.1-3
3.1-4
>4
dbh class
AGB
BGB

(a)



volume per ha
0.6
0.5
0.4
0.3
0.2
0.1
0
0-5
5.1-10
10.1-15
>15
dbh class
V



(b)

FIGURE 4: Distribution of volume and biomass per ha by diameter classes in Itigi thicket (a) thicket species (b) tree species

DISCUSSION

Many studies in Tanzania reported volume and biomass for different forest vegetations, for example; Chamshama *et al*. (2004); Mwakalukwa *et al.* (2014); Malimbwi and Chamuya (2015) however, volume and biomass of thicket vegetation have not yet reported. Volume and biomass of thicket and tree species presented in this study probably are the first ones to be reported for thicket vegetation. And the methodological approach used to estimate volume and biomass for thicket clump is consistent and reliable as compared to the approach of NAFORMA. The selection of sample plots for data collection was based on random sampling that secure the data to be as representative as possible. Thus, data with wide ranges regarding different sizes were covered (Table 1).

This study reported a total of 28 thicket and tree species. According to Fanshawe (1971) and Almond (2000) cited in WWF (2014), there were 100 woody species in Itigi thicket characterized by *Baphia burttii, B. massaiensis, Bussea massaiensis, Burttia prunoides, Combretum celastroides*, *Grewia burttii*, *Pseudoprosopsis fischeri,* and *Tapiphyllum floribundum* (White 1983). Thus the number of woody species reported in this study is relatively lower compared to that reported in the same area by WWF (2014). This was most likely because the WWF aimed to capture all plant species available ecologically irrespective of abundance while this study is more likely to catch the big contributors for volume and biomass.

Based on the results, thicket species were most woody species contributor in term of abundance, volume and biomass in Itigi thicket. This was revealed by four thicket species (*P. fischeri* and *C. celastroides*, *D. cinerea* and *B. massaiensis*) found to contribute high in the area (Figure 2). Moreover, this study observed few number of tree species with diameter between 0 - 5.0 and > 10.0cm (Appendix 4 (a)). Similarly, Mligo (2012) and Sharma *et al*. (2014) reported anthropogenic activities as possible major contributors to lower number of tree species in forest.
According to Makero and Kashaigili (2016), pole cutting was among the dominating anthropogenic activity observed in Itigi thicket. Since pole cutting is selective in terms of species and size, this might also be a cause that contributed to low number of tree species in Itigi thicket. In the study area, poles were cut to the minimum of 3cm dbh, this might be low as compared to other vegetation like miombo woodland that poles were cut to the minimum of 10cm dbh.

Like other vegetation types, Itigi thicket has spatial volume and biomass stocks variability in species because of variations in stems per ha and sizes (Appendix 3 (b) and 4 (b)). In addition, anthropogenic activities could also increase this variation, since small diameters woody species were cut for poles and larger diameters woody species were harvested for charcoaling and lumbering (Makero and Kashaigili, 2016). It is very possible that the volume and biomass of woody species of thicket and tree species in Itigi thicket would be higher if this vegetation had not been subjected to anthropogenic disturbances. It was argued by Brown (1997) that forests that have been subjected to anthropogenic disturbances tend to have lower woody stocks than their potential.

The average volume estimate for example in miombo woodland in Tanzania estimated by NAFORMA is 55 m^3 per ha, in Kitulangalo Forest Reserve estimated by Malimbwi *et al*. (1994) is 38.70 m^3 per ha, Chamshama *et al.* (2004) estimated 76.03 m^3 per ha. Also the average AGB estimated in miombo woodland for example in Kitulangalo Forest Reserve estimated by Malimbwi *et al*. (1994) is 32.90 t per ha, Chamshama *et al*. (2004) estimated 41.04 t per ha and the average volume reported by Malimbwi *et al*. (1994) in bushland in Tabora is 17 m^3 per ha and in bushland in Iringa is 25 m^3 per ha, this indicating that the stocking level of volume and biomass in Itigi thicket is lower than that in miombo woodland and other bushland. Surprising, the number of stems in Itigi thicket is larger than that reported in some miombo woodlands, for example Malimbwi *et al*. (1994) reported 460 stems per ha and Chamshama *et al*. (2004) reported 1027 stems per ha in Kitulangalo Forest Reserve.

The values of AGB for thicket and tree species are larger compared to those of volume (Table 3). This does not mean that, the basic density for thicket and tree species in Itigi thicket are greater than one. This effect is most likely due to methodological approach. Computation of biomass for individual thicket clump and tree included stem, branch and twig sections while computation of volume for individual thicket clump and tree included stem and branch sections only. Therefore, inclusion of twigs when computing volume would improve the volume estimate. Unfortunately, data that permit the calculation volume for twigs was not collected.

CONCLUSIONS

Itigi thicket is characterised by few number of woody species. Despite the scarcity of large diameter trees, the vegetation has larger number of stems per ha and reasonable amount of volume and biomass per ha. Thus, this vegetation needs to be managed sustainably.

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APPENDIX 1. Code of thicket and tree species in Itigi thicket

SN	Name	Family	Plant form
1	*Albizia petersiana*(Bolle) Oliv	Apocynaceae	Tree
2	*Baphia massaiensis* Taub.	Leguminosae	Thicket
3	*Boscia minimifolia* Chiov	Leguminosae	Tree
4	*Burttia prunoides* Baker f. & Exell	Connaraceae	Thicket
5	*Canthium burtii* Bullock sensu R. B. Drumm	Connaraceae	Tree
6	*Cassipourea mollis* (R. E. Fr.) Alston	Rhizophoraceae	Tree
7	*Combretum celastroides*.Laws	Combretaceae	Thicket
8	*Combretum fragrans* F. Hoffm	Combretaceae	Thicket
9	Combretum molle G.Don	Combretaceae	Tree
10	*Combretum paniculatum*.Vent	Combretaceae	Thicket
11	*Combretum zeyheri*.Sond	Combretaceae	Tree
12	*Commiphora Africana* (A. Rich.) Engl.	Burseraceae	Tree
13	*Croton scheffleri* Pax	Euphorbiaceae	Thicket
14	*Dalbergia boehmii*.Taub	Euphorbiaceae	Tree
15	*Dicrostachys cinerea*.(L) Wight & Arn	Fabaceae	Thicket
16	*Grewia forbesii* Harv.ex Mast.	Tiliaceae	Thicket
17	*Grewia similis* K.Schum	Tiliaceae	Thicket
18	*Haplocoelum foliolosum*(Hiern) Bullock	Sapindaceae	Tree
19	*Lannea fulva* (Engl.) Engl.	Anacardiaceae	Tree
20	*Maerua triphylla*A. Rich. subsp. pubescens (Klotzsch) DeWolf	Capparaceae	Thicket
21	*Pseudoprosopis fischeri*.(Taub) Harms	Bignoniaceae	Thicket
22	*Senna singueana* (Delile) Lock	Oleaceae	Tree
23	*Strophanthus eminnii* Asch.& Pax ex Pax	Oleaceae	Tree
24	*Tennantia sennii* (Chiov.) Verdc. & Bridson	Rubiaceae	Thicket
25	*Tricalysia* A. Rich. ex DC	Rubiaceae	Tree
26	*Vangueria madagascariensis* J.F. Gmelin	Rubiaceae	Tree
27	*Vitex mombassae* Vatke	Lamiaceae	Tree
28	*Zanthoxyllum chalebium*Engl	Lamiaceae	Thicket

APPENDIX 2. Statistics of stand parameters for Itigi thicket

Plot	N	G	tAGB/ha	tBGB/ha	V/ha
1	12468	3.3	7.0	4.3	10.0
2	8831	3.0	16.6	7.1	13.0
3	17403	7.6	42.7	15.8	28.9
4	14221	4.4	10.3	4.5	13.7
5	4416	1.2	6.2	2.5	5.4
6	5000	3.3	24.5	12.3	16.5
7	260	0.0	0.0	0.0	0.0
8	0	0.0	0.0	0.0	0.0
9	65	0.0	0.1	0.0	0.0
10	0	0.0	0.0	0.0	0.0
11	5260	1.2	3.6	1.0	2.0
12	4610	1.2	3.3	1.3	4.2
13	65	0.0	0.1	0.0	0.0
14	8766	2.2	6.8	2.1	5.8
15	7143	3.4	13.0	6.0	11.6
16	5455	2.3	10.3	5.2	8.3

Plot	N	G	tAGB/ha	tBGB/ha	V/ha
17	10714	5.1	28.3	13.7	23.5
18	9221	4.3	22.3	10.4	20.5
19	8182	1.4	4.3	2.8	4.9
20	8506	2.7	8.3	3.2	7.7
21	195	0.0	0.1	0.0	0.1
22	130	0.0	0.1	0.0	0.1
23	11299	2.0	5.6	2.7	6.4
24	12922	10.0	51.5	31.8	36.1
25	10974	3.7	14.8	7.7	15.3
26	8766	3.7	24.1	9.3	21.1
27	6234	2.1	11.5	5.4	9.3
28	0	0.0	0.0	0.0	0.0
29	9805	1.9	4.7	2.5	7.1
30	5455	1.3	12.3	4.1	8.7
31	9610	1.7	4.0	2.3	4.7
32	5130	3.3	15.4	7.6	13.9
33	0	0.0	0.0	0.0	0.0
34	0	0.0	0.0	0.0	0.0
35	0	0.0	0.0	0.0	0.0
36	5974	1.3	2.9	1.4	4.0
37	325	0.0	0.6	0.1	0.3
38	3312	1.2	5.1	1.4	4.6
39	0	0.0	0.0	0.0	0.0
40	0	0.0	0.0	0.0	0.0
41	22727	9.5	35.6	16.6	32.5
42	12013	6.1	13.9	6.9	14.2
43	25844	8.6	16.1	7.7	22.0
44	14935	5.2	12.2	6.0	15.8
45	20909	7.5	17.6	8.8	22.0
46	9091	3.7	9.2	3.9	10.3
47	9740	5.2	23.4	9.6	20.1
48	5844	1.7	5.8	2.7	6.4
49	11104	5.9	26.2	12.3	22.5
50	5584	3.4	16.9	7.8	14.9
51	10130	3.1	13.6	5.8	11.7
52	7403	5.9	21.7	10.3	20.9
53	13377	5.0	21.0	9.9	20.3
54	12532	3.7	6.8	4.3	11.6
55	14675	6.4	31.4	14.8	28.4
56	0	0.0	0.0	0.0	0.0
57	4870	1.6	5.2	2.9	6.2
58	0	0.0	0.0	0.0	0.0

Plot	N	G	tAGB/ha	tBGB/ha	V/ha
59	0	0.0	0.0	0.0	0.0
60	0	0.0	0.0	0.0	0.0
61	0	0.0	0.0	0.0	0.0
62	0	0.0	0.0	0.0	0.0
63	0	0.0	0.0	0.0	0.0
64	0	0.0	0.0	0.0	0.0
65	0	0.0	0.0	0.0	0.0
66	6494	3.7	16.8	6.8	12.0
67	5000	2.3	13.1	5.6	9.7
68	10779	5.2	15.3	6.0	16.8
69	0	0.0	0.0	0.0	0.0
70	0	0.0	0.0	0.0	0.0
71	0	0.0	0.0	0.0	0.0
72	0	0.0	0.0	0.0	0.0
73	0	0.0	0.0	0.0	0.0
74	0	0.0	0.0	0.0	0.0
75	0	0.0	0.0	0.0	0.0
76	6818	4.0	18.9	10.2	17.6
77	16429	4.6	20.4	7.6	22.7
78	0	0.0	0.0	0.0	0.0
79	0	0.0	0.0	0.0	0.0
80	0	0.0	0.0	0.0	0.0
81	4416	1.1	3.8	1.6	2.6
82	4610	1.2	3.3	1.3	4.2
83	260	0.0	0.7	0.1	0.4
84	7922	2.1	6.6	2.0	5.6
85	6623	3.4	12.8	6.0	11.4
86	4935	0.9	3.7	1.8	2.7

Appendix 3. Stems per ha, basal area, volume and biomass for thicket species in different dbh classes

(a) Stems per ha and basal area of thicket

	Dbh class (cm)										Total	
	0-1		**1.1-2.0**		**2.1-3.0**		**3.1-4.0**		**>4**			
Species name	**N**	**G**	**N**	**G**	**N**	**G**	**N**	**G**	**N**	**G**	**N**	**G**
Baphia massaiensis Taub.	7	0.001	100	0.025	42	0.016					149	0.041
Burttia prunoides Baker f. & Exell	1	0.000			18	0.010					19	0.010
Combretum celastroides.Laws	9	0.000	355	0.082	630	0.328	404	0.428	92	0.136	1490	0.975
Combretum fragransF. Hoffm			5	0.001							5	0.001
Combretum paniculatum.Vent	14	0.001	58	0.010	13	0.006					85	0.017
Croton scheffleri Pax	8	0.001	100	0.026							108	0.026
Dicrostachys cinerea.(L) Wight & Arn	45	0.002	94	0.015							140	0.017
Grewia forbesii Harv.ex Mast.	3	0.000	194	0.040	137	0.067					334	0.108
Grewia similis K.Schum	14	0.001	157	0.031	48	0.030	17	0.016	4	0.006	239	0.084
Maerua triphyllaA. Rich. subsp. pubescens (Klotzsch) DeWolf	18	0.001	32	0.006	20	0.013					70	0.020
Pseudoprosopis fischeri.(Taub) Harms	185	0.015	2295	0.475	570	0.234					3050	0.724
Tennantia sennii(Chiov.) Verdc. & Bridson			4	0.001							4	0.001
Zanthoxyllum chalebiumEngl	11	0.001	32	0.005							42	0.006
Mean	**315**	**0.023**	**3425**	**0.716**	**1478**	**0.704**	**421**	**0.445**	**96**	**0.142**	**5735**	**2.030**

N=stems per ha, G= basal area per ha

(b) Above- and belowground biomass of thicket

Name	Dbh class (cm)										Total	
	0-1		1.1-2.0		2.1-3.0		3.1-4.0		>4			
	tAGB/ha	tBGB/ha	tAGB/ha	tBGB/ha	tAGB/ha	tBGB/ha	tAGB/ha	tBGB/ha	tAGB/ha	tBGB/ha	tAGB/ha	tBGB/ha
Baphia massaiensis Taub.	0.002	0.001	0.051	0.036	0.039	0.04					0.09	0.08
Burttia prunoides Baker f. & Exell	0	0			0.073	0.023					0.07	0.02
Combretum celastroides.Laws	0.003	0	0.33	0.063	1.444	0.461	2.421	1.115	1.083	0.61	5.28	2.25
Combretum fragransF. Hoffm			0.015	0.002							0.01	0
Combretum paniculatum.Vent	0.01	0.001	0.093	0.014	0.062	0.019					0.16	0.03
Croton scheffleri Pax	0.004	0	0.059	0.019							0.06	0.02
Dicrostachys cinerea.(L) Wight & Arn	0.011	0.003	0.055	0.035							0.07	0.04
Grewia forbesii Harv.ex Mast.	0	0	0.117	0.023	0.211	0.076					0.33	0.1
Grewia similis K.Schum	0.007	0.001	0.098	0.02	0.131	0.044	0.076	0.036	0.1	0.05	0.41	0.15
Maerua triphyllaA. Rich. subsp. pubescens (Klotzsch) DeWolf	0.008	0.001	0.048	0.007	0.063	0.021					0.12	0.03
Pseudoprosopis fischeri.(Taub) Harms	0.027	0.02	0.843	0.536	0.336	0.275					1.21	0.83
Tennantia sennii(Chiov.) Verdc. & Bridson			0.009	0							0.01	0
Zanthoxyllum chalebiumEngl	0.002	0	0.017	0.003							0.02	0
Grand Total	**0.07**	**0.03**	**1.73**	**0.76**	**2.36**	**0.96**	**2.5**	**1.15**	**1.18**	**0.66**	**7.8**	**3.6**

tAGB=ton of aboveground biomass per ha, tBGB=ton of belowground biomass per ha

(c) Volume of thicket

Name	Dbh class (cm)					Total
	0-1	1.1-2.0	2.1-3.0	3.1-4.0	>4	
	V	V	V	V	V	V
Baphia massaiensis Taub.	0.002	0.094	0.059			0.16
Burttia prunoides Baker f. & Exell	0.000		0.043			0.04
Combretum celastroides.Laws	0.001	0.230	1.061	1.801	0.701	3.80
Combretum fragransF. Hoffm		0.009				0.01
Combretum paniculatum.Vent	0.005	0.048	0.027			0.08
Croton scheffleri Pax	0.001	0.035				0.04
Dicrostachys cinerea.(L) Wight & Arn	0.008	0.060				0.07
Grewia forbesii Harv.ex Mast.	0.000	0.091	0.161			0.25
Grewia similis K.Schum	0.004	0.062	0.100	0.060	0.052	0.28
Maerua triphyllaA. Rich. subsp. pubescens (Klotzsch) DeWolf	0.003	0.030	0.047			0.08
Pseudoprosopis fischeri.(Taub) Harms	0.042	1.549	0.761			2.35
Tennantia sennii(Chiov.) Verdc. & Bridson		0.006				0.01
Zanthoxyllum chalebiumEngl	0.001	0.010				0.01
Grand Total	**0.07**	**2.22**	**2.26**	**1.86**	**0.75**	**7.2**

V=volume per ha

Appendix 4. Stems per ha, basal area, biomass and volume of tree species in different dbh classes

(a) Stem density and basal area of tree species

Name	Dbh class (cm)								Total	
	0-5.0		5.1-10.0		10.1-15.0		>15			
	N	G	N	G	N	G	N	G	N	G
Canthium burtii Bullock sensu R. B. Drumm			2	0.006	1	0.011			2	0.017
Cassipourea mollis (R. E. Fr.) Alston			2	0.007					2	0.007
Combretum molle G.Don			1	0.005					1	0.005
Combretum zeyheri.Sond			1	0.004			1	0.020	2	0.025
Commiphora africana(A. Rich.) Engl.			2	0.009					2	0.009
Dalbergia boehmii.Taub			5	0.020					5	0.020
Haplocoelum foliolosum(Hiern) Bullock			5	0.020					5	0.020
Lannea fulva (Engl.) Engl.			2	0.009	2	0.018			3	0.027
Senna singueana (Delile) Lock	1	0.001	2	0.008	1	0.008			3	0.017
Strophanthus eminnii Asch.& Pax ex Pax	2	0.002							2	0.002

Name	Dbh class (cm)								Total	
	0-5.0		5.1-10.0		10.1-15.0		>15			
	N	G	N	G	N	G	N	G	N	G
Tricalysia A. Rich. ex DC	1	0.001							1	0.001
Vangueria madagascariensis J.F. Gmelin			2	0.005	1	0.006			2	0.011
Vitex mombassae Vatke	1	0.001							1	0.001
Mean	**4**	**0.004**	**21**	**0.099**	**4**	**0.044**	**2**	**0.034**	**30**	**0.181**

N=stem density per ha, G= basal area per ha

(b) Above and belowground biomass of tree species

Name	Dbh class (cm)								Total	
	0-5.0		5.1-10.0		10.1-15.0		>15			
	tAGB/ha	tBGB/ha	tAGB/ha	tBGB/ha	tAGB/ha	tBGB/ha	tAGB/ha	tBGB/ha	tAGB/ha	tBGB/ha
Albizia petersiana(Bolle) Oliv			0.029	0.015					0.03	0.02
Boscia minimifolia Chiov							0.057	0.026	0.06	0.03
Canthium burtii Bullock sensu R. B. Drumm			0.033	0.020	0.047	0.022			0.08	0.04
Cassipourea mollis (R. E. Fr.) Alston			0.038	0.022					0.04	0.02
Combretum molle G.Don			0.025	0.014					0.02	0.01
Combretum zeyheri.Sond			0.023	0.013			0.073	0.031	0.10	0.04
Commiphora africana(A. Rich.) Engl.			0.052	0.030					0.05	0.03
Dalbergia boehmii.Taub			0.114	0.065					0.11	0.07
Haplocoelum foliolosum(Hiern) Bullock			0.111	0.064					0.11	0.06
Lannea fulva (Engl.) Engl.			0.046	0.025	0.080	0.039			0.13	0.06
Senna singueana (Delile) Lock	0.006	0.004	0.044	0.025	0.037	0.018			0.09	0.05
Strophanthus eminnii Asch.& Pax ex Pax	0.015	0.011							0.02	0.01
Tricalysia A. Rich. ex DC	0.006	0.004							0.01	0.00
Vangueria madagascariensis J.F. Gmelin			0.030	0.018	0.031	0.016			0.06	0.03
Vitex mombassae Vatke	0.005	0.004							0.01	0.00
Grand Total	**0.033**	**0.024**	**0.545**	**0.311**	**0.195**	**0.096**	**0.130**	**0.057**	**0.90**	**0.49**

tAGB=ton of aboveground biomass per ha, tBGB=ton of belowground biomass per ha

(c) Volume of tree species

Name	dbh class (cm)				Total
	0-5.0	**5.1-10.0**	**10.1-15.0**	**>15**	
	V	**V**	**V**	**V**	**V**
Albizia petersiana(Bolle) Oliv		0.019			0.02
Boscia minimifolia Chiov				0.064	0.06
Canthium burtii Bullock sensu R. B. Drumm		0.031	0.051		0.08
Cassipourea mollis (R. E. Fr.) Alston		0.028			0.03
Combretum molle G.Don		0.031			0.03
Combretum zeyheri.Sond		0.027		0.048	0.08
Commiphora africana(A. Rich.) Engl.		0.059			0.06
Dalbergia boehmii.Taub		0.108			0.11
Haplocoelum foliolosum(Hiern) Bullock		0.118			0.12
Lannea fulva (Engl.) Engl.		0.045	0.081		0.13
Senna singueana (Delile) Lock	0.006	0.051	0.038		0.09
Strophanthus eminnii Asch.& Pax ex Pax	0.015				0.01
Tricalysia A. Rich. ex DC	0.005				0.00
Vangueria madagascariensis J.F. Gmelin		0.034	0.030		0.06
Vitex mombassae Vatke	0.005				0.00
Grand Total	**0.030**	**0.551**	**0.200**	**0.113**	**0.89**

V=volume per ha