EXAMINING FOREST STRUCTURE IN THE MOZAMBICAN MIOMBO WOODLANDS UTILIZING IN-SITU AND REMOTELY SENSED MEASUREMENTS AND OBSERVATIONS

Ethan Koesters Heil

Department of Environmental Sciences
University of Virginia

Abstract

Land use change in the form of deforestation and degradation is contributing to the release of greenhouse gases on the order of 1.2 ±0.7 Gt CO2e per year. Emissions of this magnitude suggest that the conversion and disturbance of forests play a significant role in forcing global climate change. Although there is growing recognition of this contribution among scientific and political communities, there is an expressed need for more efficient and accurate methods for understanding the role of forests in shifting climate patterns. Recent efforts to measure and monitor forests on large scales have leveraged remotely sensed data from airborne and spaceborne sensors. This study aims to leverage high spatial resolution, remotely sensed data in conjunction with in-situ field measurements to measure forest structure in the Miombo woodlands of Mozambique. An emphasis on this topic is motivated by the importance of three-dimensional forest structure in driving forest dynamics. A novel tree crown analysis methodology will be employed in order to discern various structural properties of forests from remotely sensed data. The results of this approach will in turn be used to evaluate and compare the effects of different forest utilization practices on forest structure.

1 Introduction

1.1 Forests as part of a global system

Forests play a unique and dynamic role in a complex global system. These distinctive ecosystems provide a vast array of essential functions as part of broader environmental, social, economic and political systems. Forest ecosystems are often viewed in terms of the tangible environmental goods and services they provide, which can subsequently be divided into timber or non-timber concerns. Timber products are explicitly associated with forests, and refer to lumber and other goods (such as paper) which trace their material roots back to trees. Services provided by the consumption of timber range from the localized heating provided by small campfires to the electricity provided by industrial-scale wood pellet-based power plants. Forest ecosystems also provide countless non-timber (and often less obvious) goods and services ranging from habitat preservation and shelter to nutrient and chemical cycling. While the benefits of forests are numerous, in certain forested areas, economic, social and political pressures are contributing to unsustainably extractive and destructive practices. Meanwhile, increasing recognition of the broad, essential roles of forests is contributing to concerns over the potential long-term negative consequences associated with these actions.

In light of growing concerns regarding the role of greenhouse gases in forcing global climate change, understanding the movement of carbon through forest ecosystems is becoming increasingly important. The link between forests and climate change forcing is compelling with as much as 12-20% of global anthropogenic carbon emissions resulting from deforestation and land use change. Essentially, these emissions come from the
conversion of carbon stocks as a sequestered form of vegetative biomass into greenhouse gases such as carbon dioxide and methane. To better understand and manage the carbon balance of terrestrial ecosystems, more information is needed about how biomass is being released in the form of atmospheric greenhouse gases and how these emissions can be mitigated. Efforts at quantifying carbon emissions due to deforestation and land use change are still evolving and lacking in empirical rigor. This is illustrated by significantly larger percentage uncertainty associated with greenhouse gas emissions due to deforestation (1.2 ±0.7 Gt CO$_2$e/a) as compared to those due to fossil fuel use (8.7 ±0.5 Gt CO$_2$e/a). Additionally, an imbalance in the global carbon budget has led to speculations of a 1.6 Gt C/a unidentified terrestrial sink. Ideally, the application of new and more expansive methods for measuring carbon cycling in terrestrial ecosystems will lead to a reduction in this uncertainty and inform attempts to reduce future emissions.

The emergence of new methodologies for measuring and monitoring forest ecosystems coincides with greater awareness of global climate change and other large-scale, human-induced ecological shifts. As such, there is a broad-based social, economic, political and scientific movement to leverage these methods to enhance understanding of the role of forests and learn how to manage them in a sustainable, mutually beneficial manner. The aim of this research is to contribute incrementally to this much larger movement by examining forest structure in a relatively understudied area in the Miombo woodlands of Mozambique. Accordingly, this research intends to develop and employ a suitable methodology for measuring forest structural properties using a combination of in-situ data collection and high resolution remote sensing analysis. This will in turn allow for a comparative analysis of forest structure among sites that experience varying degrees of anthropogenic forest disturbance, including: preserved forests, community-use forests, traditionally extractive commercial logging operations, and an innovative, sustainable use forestry.

1.2 Tropical forests and land use change

Land use change, particularly in the context of deforestation, refers to the intentional removal of forests. For thousands of years, land use change has been driven by the desire to increase arable or pastoral agricultural land and make room for settlement. Deforestation also comes from resource extraction, wherein trees or other vegetation is removed in a manner that alters the original forest ecosystem. Degradation refers to less visible forest disturbances in the form of selective logging or understory livestock grazing. The result of deforestation and degradation is the disruption of natural forest processes with broad ranging implications that can take decades or centuries to recover. Among the most significant effects of deforestation and degradation, is the release of greenhouse gases. As forests are cleared or disrupted, sequestered carbon within terrestrial biomass and soil is released through decomposition, fire, tilling and other anthropogenic activities. As previously noted, up to one fifth of all anthropogenic greenhouse gas emissions are due to land conversion practices and deforestation. Additional climate forcing affects associated these practices include the alteration of albedos by changing the reflectance characteristics of landscapes and introducing black carbon to the atmosphere through biomass burning.

Although land-use changes are occurring on a global scale, about 60% of the carbon dioxide emissions from these activities occur in the form of deforestation within the tropics.
The reasons behind the aforementioned trends in deforestation and land use change are complex, and are subject to a variety of political, social, economic and environmental influences. For many, forested lands are viewed as a resource, whether as a potential field for pastoral grazing, a bank of harvestable timber or a preserve of biodiversity. Regardless of viewpoint, it is important to understand not only what role forests play in changing global systems, but also how they in turn respond to such changes.

1.3 The role of remote sensing

The burgeoning age of remote sensing, is providing new methods of measurement on scales that would have previously seemed impossible. Remote sensing techniques allow researchers to analyze data on spatial and temporal scales that are often orders of magnitude greater than that which could be similarly analyzed from an in-situ perspective. As such, remote sensing applications are well-suited to contribute to research on global climate change and its effects, ranging from measuring atmospheric and sea surface temperatures to monitoring changes in polar ice mass.

Remote sensing techniques can additionally be used to observe and monitor terrestrial processes that dynamically interact with the global climate. In particular, there exists a promising array of remote sensing methods that can be employed to measure and monitor forests. While all of these techniques rely on measuring the forests’ interaction with and reflection of electromagnetic radiation, a wide variety of variables and otherwise helpful metrics can be gathered through remote sensing. Some methodologies provide simple Boolean classification of forested versus nonforested areas, while others allow for measurement of actual geophysical values such as the fraction of Absorbed Photosynthetically Active Radiation (fAPAR) or crown geometry.

There are a growing number of terrestrial remote sensing techniques that provide various tradeoffs in terms of accuracy, spatial resolution, spatial extent, and temporal span. These methods, in turn, provide insight into a variety of forest characteristics, including changes due to anthropogenic degradation, productivity, phenology, senescence, biodiversity, and forest structure. This study uses methods for measuring forest structure and related properties, which are expounded in section 1.5.

1.4 Importance of forest structure

Remote sensing methods for monitoring and measuring forests are useful in quantifying the role of forests as part of broader societal issues, including climate change and biodiversity preservation. In order to frame forests within these contexts, several forest metrics have become increasingly important as part of global, transdisciplinary discussions. One such metric is the measurement of forest biomass, which provides crucial insight into the flow and stores of carbon within forest ecosystems.

Forest biomass provides a measurement of sequestered carbon (in mass units) and includes organic matter in the form of above and below ground living vegetation (trees, shrubs, saplings, vines, etc) as well as dead vegetation (leaf litter, downed logs, etc). Obtaining reasonable estimates for below ground biomass and dead vegetation is extremely difficult with current techniques, and is often time and cost prohibitive. As such, the majority of biomass estimates focus on above ground living biomass (AGB), which includes standing vegetation such as leaves, stems, branches, vines, trunk and bark. AGB is generally regarded as containing the majority of biomass within forests (though some particular trees have been shown to contain more below ground biomass than above ground) and is assumed to be a good proxy for total biomass. It should be noted
that current measurements of biomass rarely take into account the significant quantities of carbon stored within the soil substrate.

Given the role of carbon in the context of global climate change, it becomes clear why biomass is an important variable. Unfortunately, the in-situ measurement of these variables is often prohibitively expensive and tedious. As such, efforts have been made to correlate remote sensing and in-situ measures. While this seems like a promising approach, these methods do not allow for direct measurement of biomass or productivity and tend to rely on correlations and relationships among pixel reflectance values.

In recognition of such limitations, the National Research Council Committee on Earth Science and Applications from Space calls for the incorporation of forest structure into remote sensing analyses of forests as a top priority. Many current methodologies are limited by their reliance on a two dimensional conceptualization of forests. In the manner of form influencing function, the three dimensional structure of a forest plays a significant role in determining forest processes. The converse, which states function also influences form, highlights the notion that forest structure will in turn adapt as forest processes change. Incorporating the influence of horizontal and vertical forest structure in scientific studies will thus allow for a better understanding of forest dynamics. As such, measurements based on the inclusion of forest structure have the potential to greatly reduce uncertainty in measurements of forest biomass, carbon cycling, productivity, energy balance and even habitat diversity.

1.5 Remote sensing of forest structure

Current methods for measuring forest structure generally fall into the following categories: field measurement methods, remote sensing methods, and geographic information systems (GIS) methods (Lu, 2006). Each of these methods has their respective strengths and limitations. Field measurement-based methodologies of measuring structure are generally regarded as the most accurate, but require significant amounts of time, expertise, manpower and equipment - which all in turn translate to a prohibitive financial burden for monitoring anything other than small measurement plots. That being said, field-based measurement are often required in one form or another in order to calibrate, validate and/or verify observations using other techniques such the GIS-based or remote sensing-based approaches. GIS-based approaches have been used to some degree in the past because of the ease in obtaining the required inputs for this sort of inventory. GIS-based estimates rely on land cover classification maps that relate different types of land cover to different forest structure estimations. These estimates often do not require extensive expertise and monetary resources and allow underresourced, developing countries to self-report their land classification. While promoting national sovereignty, these methods are not standardized and are often riddled with uncertainty, inconsistency, and misclassification of land cover type.

Remote sensing methods provide alternatives to some of the issues raised by field-based and GIS-based method, but there is currently no “best method” for remote sensing of forest structure. In fact, there are a whole slew of approaches, each with their own respective strengths and weaknesses. They can be broken up into four broad categories including: fine spatial resolution (fine-scale) passive approaches, medium spatial resolution (medium-scale) passive approaches, coarse spatial resolution (coarse-scale) passive approaches, and active remote sensing approaches. The nature of these different methods is such that there are tradeoffs in temporal and spatial resolution, availability and cost at each scale. Due to
various factors, including the remote location of this study’s area of interest and the need to analyze forest structure at fine scales, this research leverages fine-scale passive remotely sensed data.

1.6 Dry tropical forests

Dry tropical forests (as compared to wet and moist tropical forests) comprise the biggest proportion of tropical forests and represent an estimated 22% of the Earth’s total forests. Given its relative abundance compared with wet tropical forests, the dry tropical forest biome receives much less public, media, and scientific attention. This type of forest appears to be understudied due to both methodological and economic factors. From a remote sensing point of view, this likely has to do with the complexity inherent in the assessment of dry tropical forests. This includes difficulties measuring multi-story canopies and surface reflectance issues. In addition, existing algorithms are typically designed either for less complex temperate, or more complex moist biomes that saturate when applied to dry tropical rainforests. Many dry tropical forests fall within the boundaries of relatively under-resourced and developing countries, complicating data collection. In developing countries, scientific endeavors compete for limited resources and are often relegated on the list of priorities, while a lack of developed infrastructure makes in-situ studies more difficult and costly. This study offers the opportunity to provide data on a region of forests that is under-researched.

2 Project Description

2.1 Research Questions

1. (a) Can remote sensing analysis utilizing crown delineation software effectively identify and measure tree crowns in a manner consistent with in-situ data? (b) Can this methodology be successfully employed over the range of forest types (from open woodlands to closed canopy) found within the Miombo woodlands? 2. Using this analysis, will there be detectable and significant structural dissimilarities in forests that undergo different disturbance regimes? 3. Will this methodology be able to link changes in forest structure to various forest management practices?

2.2 Study Area

The study area is located within the Miombo woodland ecological region, approximately 30 kilometers south of the Zambezi River within the Cheringoma District, in the Sofala Province of Mozambique. Figure 1 displays the study area overlaid on a land cover map that illustrates the three main land classifications present, including dense forests, open woodlands and prairies. This particular site was chosen for a number of reasons, in part because of the relatively understudied and remote nature of this area. Additionally, research within this study area was chosen to leverage and strengthen preexisting, longitudinal relationships among researchers at the University of Virginia, the University of Southern Illinois and the University of Eduardo Mondlane in Maputo, Mozambique and the operators of the timber concession, TCT Catapu, in the Sofala Province of Mozambique. In particular, as one of only two Forest Stewardship Council (FSC) certified operations in Mozambique, and only a handful within the entire African continent, TCT Catapu offers a uniquely managed, periodically-disturbed forest unlike anywhere else on the continent. A site visit in 2009 confirmed the novel and sustainable practices being employed by this operation, including the designation of 16 hectare unmanaged and unharvested “set aside areas” per 1000 hectares and a 32 year, selective logging rotation among different blocks within the property. This type of rotation harvesting
creates a spectrum of blocks that exhibit varying and predictable amounts of time since the most recent harvesting disturbances. Lastly, the owners of this forestry have been known to welcome scientific teams on their property and can provide the local assistance necessary for conducting field research in a foreign location.

![Figure 1: Land cover map of the Sofala province adapted from Macuacua (2012) with the study area outlined in red. The legend lists the various “classes dominantes” (ruling classes) of this area.]

In addition to main site described above, subsequent forest sites will be selected for the latter, remote sensing-based analysis. At least one site that exhibits more traditional, non-certified timber harvesting techniques will be chosen in addition to at least one protected area site that prohibits any commercial logging and therefore is subject mostly to natural disturbances. Care will be taken to choose the most “similar” forests to those where in-situ data will be collected. Criteria for selection of these additional sites will include geographic proximity, forest type and precipitation gradient.

3 Methods

3.1 Data acquisition

After the specific sites were successfully selected, the data collection phase began. The two main sources of data for the proposed research can be categorized either as in-situ field data or as remote sensing data. Each of these datasets requires a distinct methodology for collection which is outlined in the following paragraphs.

In-situ data collection is an essential step in this study for two main reasons. First, in-situ data will be used to calibrate and validate subsequent analytical tools. Secondly, it will provide the basis for developing a series of allometric relationships. In order to ensure that the requisite data is properly collected, a hybrid methodology, adapting those described by Broadbent et al. was employed. These studies articulate field sampling methods for collecting the measurements necessary for the calibration of remote sensing tools similar to those used in this study. A list of in-situ measurements and observations was developed which balanced the temporal and financial costs associated with collecting field data and the need for a robust dataset. Table 1 lists these properties and their associated measurement techniques.

<table>
<thead>
<tr>
<th>Tree Property</th>
<th>Measuring Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
<td>Field guides</td>
</tr>
<tr>
<td>Diameter at breast height (DBH)</td>
<td>DBH tape</td>
</tr>
<tr>
<td>Crown width</td>
<td>Laser range finder (LRF)</td>
</tr>
<tr>
<td>Crown depth</td>
<td>LRF + clinometer</td>
</tr>
<tr>
<td>Tree height</td>
<td>LRF + clinometer</td>
</tr>
<tr>
<td>Basal area of nearby trees</td>
<td>Basal area prism</td>
</tr>
<tr>
<td>Basal area of taller nearby trees</td>
<td>Basal area prism</td>
</tr>
</tbody>
</table>

After arriving in country, specific plots were located in collaboration with the TCT Catapu forestry management. Two different plots were chosen within closed canopy and open woodland type forests, with one plot for each forest type be characterized as relatively...
undisturbed and have no recent history (within about forty years) of logging. Four randomized line transects of 500 meters were identified within each plot and a stratified sampling technique was employed based on DBH distribution. This sampling approach attempts to avoid an overrepresentation of smaller trees and underrepresentation of larger trees by assigning a sampling percentage to each DBH class. In this manner, the transect was traversed and a subplot designated at 25 meter intervals. At each subplot, the four nearest trees exhibiting the minimum DBH requirement (at least 10 centimeters) was selected, their DBH measured and their species noted. Each tree was then be matched with a random one digit number, which determined whether that tree’s DBH class necessitated the additional measurements presented in table 1.

Using this methodology, 16 transects were traversed for a total of 8 kilometers, over which distance 1280 trees had their species and DBH recorded. 469 of these trees were fully measured, which exceeds the suggested sample population of 300 trees for calibration presented by Asner et al.\textsuperscript{15} The DBH bin distribution of these 1280 trees are displayed in figure 2.

![Figure 2: The number of trees which fell into each DBH bin class, where DBH was measured in centimeters.](image)

An appropriate remote sensing dataset (or “image”) is a necessary complement to the in-situ data that was collected on the ground. As discussed previously, there are several general types of remote sensing data. In order to choose the most appropriate dataset for the purposes of this research, several factors were taken into account, including spectral range, spatial resolution, availability and cost. The most limiting factor was spatial resolution. Since this study is interested in analyzing the structural properties of forests at the individual tree level, remote sensing datasets with spatial resolutions larger than an average tree’s canopy were immediately excluded. The next factor to consider is the spectral range associated with each remote sensing dataset. This is a less exclusive data requirement, as the analysis software being employed is compatible with a range of spectral inputs, from panchromatic to hyperspectral and even those employing light detection and ranging (LIDAR) techniques. Cost and availability are obvious limitations associated with almost any type of data collection and that were also considerations during the acquisition process.

Although active LIDAR-based datasets are promising for this type of research because they represent measurements taken in three dimensional space, they were unavailable for this study’s area of interest. As such, this study will rely on the analysis of two-dimensional passively remote sensed images. These datasets have been proven to be effective inputs in previous tree structure analyses as long as they are of sufficient spatial resolution.\textsuperscript{14} For the purposes of this study, the remotely sensed data comes from archived images taken by the WorldView2 satellites at less than one meter spatial resolution.

3.2 Data processing

Upon successful collection of the requisite datasets, some degree of preprocessing is necessary before analysis begins in earnest. In-situ data will need to be aggregated and organized so that preliminary calculations and allometric relationships can be investigated. After the remotely sensed images are obtained, a certain degree of image preprocessing will need to occur before it can
be suitably analyzed. This will include the application of filters, masks and corrections for atmospheric, sun glint or other effects. After these steps, the maximum, minimum and modal brightness values for each image will be calculated and the image will be smoothed. A moving window filter can be used to smooth images that contain a high level of pixel-value variability, while preserving the detail necessary for further analysis. In this manner, each pixel is assigned a new value based on an average of its surrounding pixel values.  

3.3 Remote sensing analysis

A software suite employing an automated tree crown analysis algorithm will be used to analyze the aforementioned remote sensing datasets. Once the remote sensing image is appropriately preprocessed, it can be analyzed by the software, which uses pattern recognition algorithms to systematically scan the image and automatically delineate tree crowns. There are many methods that have been proven successful in delineating tree crowns, including local minima value finding, local maxima filtering, template matching, valley finding, three dimensional modeling and wavelet analysis. The specific software being used in this research leverages a combination of local minima finding and local maximum filtering. This software-based approach was chosen because of its successful use in randomly distributed, high density tropical forests, whereas other methods have focused on less dense, low diversity forests with more regular canopy geometries.

The algorithm works by receiving a geolocated, remotely sensed image as an input, then scanning and identifying local maximum values (as determined by the “brightness” of each pixel’s digital number). From these maximum value locations, an ordinal transect analysis is conducted in 360 directions in a linear transect. These transects extend a certain way before an observed drop in brightness between two adjacent pixels reaches a certain threshold and the ordinal transect is ended. The aim of the local maximum point is to be located near the center of the canopy and in turn, the ordinal transects attempt to extend radially to the edge of the tree crown and terminate. These transects are then connected and approximated as circles centered at the local maximum to delineate that individual crown. The circle’s radius is calculated as half the sum of the longest pair of opposing transects. This circle is then removed from the image as analysis continues, iteratively seeking lower local maximum values as additional “trees” are removed. After this point, the analysis is essentially over and the software outputs data on the geometry of the delineated crowns, their distributions and densities. An added benefit of using this suite is its inclusion of other analyses beyond crown delineation. These include estimates of lacunarity, entropy, angular second momentum, semi-variance and a power spectrum analysis, which can contribute to deeper understanding of canopy structure.

While the steps above will hold true for the purposes of this study, various tweaks and calibrations will likely need to be undertaken to more appropriately analyze a dataset based in the Miombo woodlands. The software suite has not yet been tested in this type of forest, but has been tested on a range of other landscapes, from Amazonian tropical forests, to the Sierra Nevada’s in California. As such, the field data collected for this study will be used as a tool to calibrate the software and ensure that the outputted results are statistically reasonable. Calibration will come in the form of adjusting the aforementioned brightness drop threshold in addition to the potential introduction of other thresholds (e.g., ignoring local maximum points above a certain value that could be due to soil reflectance) to promote more appropriate delineation. In order to ensure proper...
verification and validation, the in-situ dataset will be randomly split in half such that one half is used in this calibration procedure, while the other half is reserved for later validation.

### 3.4 Scale results

The analysis described above is limited to smaller spatial and temporal extents than those associated with medium and coarse scale imaging. This is partly because of the tradeoffs inherent in spatial versus temporal resolution. Additionally, the acquisition and analysis of these fine-scale images as described above are costly in terms of time and finances. As such, there is a growing interest in pairing fine-scale analysis with coarser-scale remote sensing products in order to evaluate larger swaths of land over more regular time periods. In order to marry the precision associated with fine-scale analysis with the extent inherent in coarser datasets, it has been suggested that coarse (MODIS or MISR) to medium-scale (Landsat) datasets be used to extrapolate fine-scale analyses over larger areas.\(^\text{17}\)

Scaling the precision of finer-scale analyses to broader extents and leveraging coarser-scale analyses to pinpoint areas for fine-scale study have been done to some degree of success.\(^\text{18}\) Although such an extrapolation technique would certainly be beneficial, there are few techniques that would apply to the specifics of this project. The authors of the software analysis suite discussed above recognize this and are engaging in efforts to develop a robust scaling technique. Efforts will be made to collaborate with them in the hopes of scaling the data in the study across wider extents.

### 3.5 Comparative analysis

The datasets will be used in a comparative analysis of at least three forest sites which are characterized by unique patterns of disturbance and land use. Using statistical analysis software, various forest structure properties (as outputted by the remote sensing analysis) will be compared to determine any significant patterns or variations that could provide insight into the research questions set forth above. Preliminary analysis of the remote sensing methodology will determine whether it is properly evaluating the landscape of interest, which will be validated using the remaining in-situ data (not used during calibration and verification). Assuming the outputted data can be successfully validated, a comparative analysis can then be undertaken to determine if there are discernable differences between sites, and if so, the extent to which distinct forest structure properties are differentially affected. Finally, several estimates of above ground biomass will be calculated using a series of allometric equations and regression models.

### 4 Anticipated outcomes and significance

In an attempt to answer the research questions set forth above, this research endeavors to contribute an incremental piece to a larger movement aimed at leveraging remote sensing techniques to monitor and measure forest ecosystems. The ideal and anticipated outcome of this study would be to prove the feasibility of using the aforementioned techniques to remotely sense and analyze forest structure in the Miombo woodlands. This study allows for an assessment of the strengths and weaknesses of applying a fine-scale, remote sensing analysis to an untried forest type, while providing subsequent studies with an additional resource for measuring forest structure.

In addition to providing methodological resources, this study aims to investigate the structural aspects of forests that have experienced different disturbance regimes. It is anticipated that different methods of anthropogenic forest use will lead in turn to measurably different forest structure.
If this is the case, it is unclear at what level this structural variation will be discernable. This study aims to evaluate whether these differences can be measured to some degree of certainty using a tree crown analysis software suite.

5 Acknowledgments
The author would like to thank the Virginia Space Grant Consortium in addition to his committee members, Dr. Robert Swap, Dr. Hank Shugart, Dr. Jennie Moody, and Dr. Michael Palace for their generous support of this research.

6 References