A Non-destructive Approach for Quantitative Assessment of Tree Resources Outside the Forest

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March, 2005
A Non-destructive Approach for Quantitative Assessment of Tree Resources Outside the Forest

by

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Thesis submitted to the International Institute for Geo-information Science and Earth Observation in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation, Specialisation: Forestry for Sustainable Development.

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Dedicated to

My Grandchild “Junior Adhikari” in Ghana
Whose parents gave their baby my name as a sign of
remembrance and love they have showed to me during the
fieldwork period
Abstract

Quantitative assessment of any resource is a first step towards its management. This also applies to the Tree Resources Outside the Forest (TROF). The heterogeneity of TROF in terms of species composition, spatial distribution and the ownership issues usually pose difficulty in its assessment using field based surveys. Besides, TROF is a dynamic resource, therefore, require more frequent assessments as compared to trees inside the forest. Assessment of the TROF in terms of volume or biomass has many advantages, especially in developing countries where fuel wood, a major product derived from TROF, is traded in weights. Biomass assessment results in a complete information of various products that can be obtained from it; be it wood, leaves, bark, or NTFPs. However, the conventional biomass assessment methods are destructive and hence, not easily applicable for TROF where repetitive assessments are required. A non-destructive volume and biomass assessment method could become relevant in such situations.

The objective of the research was to explore the potential of remote sensing techniques, combined with an existing ground-based non-destructive tree volume and biomass assessment method (Montes method), for the assessment of TROF volume in off forest reserve areas in Ghana.

The research reviewed the Montes method; a method developed to estimate volume and biomass of an individual tree using an ordinary photograph; suggested an improvement to minimize the error associated with the method by proposing a novel “model stem” method and validated the “model stem” method using a real tree example. The model stem method was then used to compute the tree volume from the tree photographs that were taken from the field. Weighted linear regression technique was used to prepare volume equation that related the tree volume with its dbh. This equation was used to estimate the plot volume in the field. The plot volume was then related with the indices that were derived from the satellite images namely ASTER and LANDSAT ETM.

The results revealed that while estimating a real tree volume, the model stem method minimized the error that occurred due to branch tilting, by as much as 10 times as compared to the Montes method. The plot volume derived from the model stem method showed significant correlation ($R^2 = 0.30$) with the Index derived from the ASTER image using ERDAS Imagine subpixel classifier.

This study concluded that (a) the model stem method is more accurate and easy to adopt as compared to the Montes method for the volume assessment of individual trees, and (b) the quantitative assessment of TROF can be done by a suitable combination of the field and satellite based remote sensing techniques which can eliminate the need for destructive sampling in future.

Keywords. Non-destructive method, model stem, sub pixel classification, Forest Canopy Density Mapper.
Acknowledgements

First and foremost, I extend my sincere gratitude to Prof. Dr. Ir. Alfred de Gier. His guidance throughout the thesis period especially during the time when I was perplexed after losing the subsampling data from the palmtop computer was enormous. His constructive criticisms, ways to simplify things with “real life” examples and “think what you write” attitude are worth mentioning. They will remain as a guidance to me for the rest of my academic and professional career. The thesis has taken this shape as a result of his deep insight and interest in this topic as it was of mine.

I also wish to express my heartfelt gratitude to Ir. Louise van Leeuwen, my second supervisor, especially for her effective guidance during the pre-field work image processing and support during the field work period in Ghana. I also wish to thank Mr. Martien Gelens, Students Adviser (FSD Specialization). You were the one to make me think about a non-destructive method for biomass assessment, Thank you Mr. Gelens! My sincere gratitude also to Dr. Yousif Hussin for his guidance in using the FCD Mapper and to Dr. Michael Weir, Programme Director NRM, for his encouragement and cooperation throughout the MSc. course here at ITC. Sincere thanks is also due to Drs. J.B. De Smeth, who helped me to use different equipments in the ITC laboratory for drying the wood samples that I collected from Ghana. Though, I was not able to use that data in this research, I am quite sure that I will use them someday in future.

I also like to thank all support staffs at ITC who were always eager to help, specially Ms. Marie Chantal who helped me to arrange the visa with little delay despite the postal carrier misplaced my passport. Thanks also to Ms. Esther Hondebrink, for helping me to arrange timely meetings with my first supervisor and the translation from French to English.

Sincere thanks also goes to all the staffs and individuals who supported me during the field work in Ghana. Mr. Francis Agurgo (RMSC), Mr Nketia & Miss Anneke (Tropenbos-Ghana), Mr. Nicholas Ayiku (DFO-Goaso), Mr Agya Owusu, Mr. Agya Nyankamako and Mr Antwi (the driver). Ms. Agnes Frempong, Mr. David and Mr. Emma deserve special thanks for making arrangement to fell the trees. Special thanks to Mr. Samuel Adu Gyamfi, a prospective leader of Ghana, who took care of me during my field work as an elder brother, and all his family who welcomed me as a member of their family; especially, brother Kwadjo should be mentioned, he made our short stay at Kumasi very delightful. May God Bless You!

Many special thanks to Ajay Bro, a YES man for me. I was always welcome whenever I knocked his door seeking some help even in the last minutes. I must also wish many thanks to Mr. Joshi, Mr. Mandal and Mr.Yadav for granting me their guardianship. Thanks to all Nepalese friends at and outside ITC for their company. Thanks to all my cluster mates for their cooperation and a feeling of teamwork we demonstrated throughout our study period. Most of the discussions, we used to have in the cluster, I hope were fruitful, though I was the one to make a lot of noise…

Finally, I am highly indebted to the Netherlands Government for granting me the fellowship under the Netherlands Fellowship Program to study at ITC without which, this study would not have been possible.

Sincerely Yours,

[Name]
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1. Introduction

1.1. Background

The term “tree resources outside forest”, generally abbreviated as TROF or TOF, covers a vast variety of formations and species growing in various combinations in rural and urban settings. FAO defines TROF as trees and shrubs occurring on land not defined as forest and other wooded land (Appendix-1). There are many ambiguities in this definition of the TROF because its definition depends on the definition of forest and other wooded lands (Kleinn, 2000) and the definitions of forest and other wooded land vary from country to country and also the boundary between what is forest and what is outside is not always clear (Kleinn, 2000; Bellefontaine, et al., 2002). For the purpose of understanding, TROF can be viewed as trees available on agricultural lands, along roads, railways, canals, ponds, orchards, parks, gardens and homestead outside the officially designated forest areas. Due to this diversity of TROF (both in terms of the resource itself and also where they occur) it is hard to assess its economic contribution at local, national or international level. Generally the products, both tangible and intangible, derived from these tree resources help contribute to sustainable agriculture, food security and rural household economies. In certain circumstances they even supply many products and services similar to forests but in different extent; for example timber, fuel wood or recreation (Kleinn, 2000; Rawat, et al., 2004). In Asia-Pacific area alone, two thirds of the energy demand is supplied by fuel wood from non-forest resources; providing fuel for two billion people (Bellefontaine, et al., 2002). They also protect crops and soil against water and wind erosion, thus combating drought and desertification as well as protect water resources (Rawat, et al., 2004). These and many other advantages of TROF justifies the importance of this resource. Realizing these and other benefits policy makers and planners now converge their thinking to acknowledge the promise of this resource as a key to sustainable development especially in developing countries like Ghana (Kotey, et al., 1998; Bellefontaine, et al., 2002).

In Ghana, forests are found in two main zones – the savannah woodlands in the north, and the tropical high forest in the south. Tropical high forest covers about seven percent of the country’s land area almost all of this forest are under a ‘reserved’ status with governments’ control. Considerable tree resources are found outside the reserves in small forest patches and trees on farms; often called off-forest reserve or TROF (Kotey, et al., 1998). After a major shift in off-reserve policy in 1994 from “liquidation” to “sustainable management”, the “off-reserve trees”, by statute, came exclusively under jurisdiction of forestry department’s management system for regulation of uncontrolled harvesting, expeditious collection of relevant fees and ultimately conformity with criteria for sustainable resource development (Kotey, et al., 1998). These policy reforms and “interim measures” (Kotey, et al., 1998) implemented thereafter, were more focussed on controlling the illegal timber harvesting outside forest reserves. But TROF that were mainly found to occur on the farm lands owned by individual farmers were not only managed by the individual farmers primarily for timber production, but also for agriculture and other forms of land on farms and fallow areas (Kotey, et al., 1998). For the purpose of
this research, despite different ambiguities, the term TROF refers to all the tree resources that occur outside the officially designated forest reserves in the study area in Ghana. A more detailed description of TROF in Ghana is in section 1.2.

1.2. TROF in Ghana

Definition of TROF, mentioned earlier in this chapter, as given by FAO means different things in different countries because of the variation in the definition of forest and woodlands in each country. Though FAO has coined a standard definition of forest and woodlands also (Appendix-2), in the real world, many countries deviate from this definition and classify their forest in own convenient way. The same holds true in Ghana also, where trees are found in two separate land management units, either on the land managed by forest department, called forest reserves or on the land managed by individual farmers, called off-reserve areas. Most of the lands outside the forest reserves have been converted to agriculture through the course of this century. The area outside forest reserves now is a mosaic of agricultural fields, fallow lands, secondary forest patches and settlements. Further classification of these off-reserve trees can be found in (Kotey, et al., 1998). For the purpose of this study, trees occurring in the area outside the officially designated forest reserve were classified as TROF. This simple definition is more appropriate for this study in Ghana. Firstly, because distinct boundary is evident between the forest reserve and off-reserve areas even in the satellite images, thus making it easy to mask out the forest reserve areas while classifying the image, secondly, due to the unavailability of aerial photographs and high resolution satellite images for e.g. IKONOS, it was not possible to see any regular pattern or configuration of TROF outside these forest reserves, making it extremely difficult to distinguish TROF based on configuration in medium resolution images like ASTER and Landsat. Literature review and preliminary reconnaissance survey in the off-reserve areas in Ghana gave a clear insight of an existence of a distinction between two vertical strata of land cover (Figure 1.1).

a) Over storey landcover, and
b) Under storey landcover

The over storey landcover is mainly composed of trees. The trees are mostly found scattered throughout the study area; with one of their main function to provide shade for under storey crops; except in few places where they are clumped together. The under storey landcover mainly consists of patches or mosaic of cocoa (new and old variety), food crops, grass and bare soil/settlements/villages. On the spatial extent, the under storey landcover patches are generally found bigger than half a hectare stretching up to many hectares, individual farmlands are about 0.5 to 1 hectares (Zhaoli, 2003), but the over storey cover i.e. the trees are found scattered throughout the area.

Figure 1.1: Vertical stratification in the off-reserve areas.
1.3. Problem Statement and Justification

For the Ghana’s Forestry commission, the primary aim to manage TROF is not the production of timber itself. However, it still provides much of country’s needed timber through overexploitation and also serves as an important source of non-timber forest products (Kotey, et al., 1998). The Forestry commission of Ghana after the implementation of the “interim measures” has tried to regulate the overexploitation of TROF by introducing a quota system which states that half of the annual timber harvest of 1,000,000m$^3$ be from the forest reserve and other half from the TROF. However, current timber harvest rate from TROF is well above this limit (Kotey, et al., 1998). It shows that, the TROF are vanishing at a faster rate.

Cocoa farmers in Ghana are replacing their farms containing old variety cocoa crop with either hybrid variety of cocoa or with oil palm (Abedi-Lartey, 2004). This conversion of landcover has direct link with the existence of trees on their farmland because both the new variety of cocoa and oil palm do not require shade from the over storey trees once they are mature. Farmers in the region therefore, are more inclined towards removing the shade trees, by ring barking, or by burning the tree (Figure 8.7 and 8.8, Appendix 14) in their cocoa farms to create a more conducive environment for these new crops to grow. This conversion in cropping pattern and lack of incentives for farmers to retain the trees in their farm, has helped to accelerate the removal of the TROF.

Off reserve inventory conducted by the Forestry department has concluded that, if the present trend of TROF harvest continues at this rate, and if it is assumed that the demand of timber in the future remains the same, with the above mentioned annual harvest limit of 500,000m$^3$, off-reserve tree resources will last for 55 years (Kotey, et al., 1998). But will the demand of timber in the mean time not rise? Is it justifiable to quantify the benefit of the TROF only in terms of timber production? After all the TROF is vanished, how will the remaining trees confined within the reserve boundaries meet the ever growing demand of timber 50 years from now? Moreover, how will the removal of the TROF affect the farms and the farming practices? What alternative resource will fulfil, the products that farmers were getting from the TROF in their farmland in their daily life once all TROF is vanished? Answering all these questions are crucial for the sustainability of TROF and the farming systems in Ghana.

Besides all these, it is also necessary to describe and comprehend the dynamics of TROF, and their interaction with forest dynamics. Understanding these dynamics leads to a better understanding of the need for TROF management and towards integrated and sustainable management of tree resources in forest reserves and off-reserves areas. The results of this kind of assessment to study the dynamics not only helps to quantify the vast amount of products TROF provide to the farmers and services to the farmland where they occur but also helps to know whether the TROF are acting to offset the shrinking tree resource base inside forest reserves (Kotey, et al., 1998; Bellefontaine, et al., 2002). This is of utmost importance in Ghana where a clear distinction in management of the tree resource inside forest and outside forest exists, where the forest reserves are primarily managed for the timber production and the disappearance of TROF can directly increase pressure on the trees inside the forests also. Therefore, understanding this dynamics is very important if the trees inside the forest reserves are to be managed for the sustainable timber production.
It is therefore, important to monitor the TROF disappearance at the first hand and to understand how the disappearance of trees outside forests affects this balance on farm and in turn on the trees inside the reserves. To understand this, it is very essential that quantitative assessments of the resource be conducted repetitively in short intervals before the resource itself vanishes and it is too late. Due to the dynamic nature of the TROF, a timely but repetitive assessment of this resource is essential for its proper monitoring and management. Repetitive assessment also helps to take immediate measures and timely amendments in the policies so as to implement these policies effectively to reduce the tree cutting and encourage tree planting outside the forest reserves. Repetitive monitoring on a long run, also helps in policy formulation for retaining the trees in the farmlands for the purpose of the carbon sequestration, as TROF can play a major role to act as carbon sinks. This kind of TROF assessment would also allow confirming locally observed trends of tree expansion or retreat, and integrating them into the farmland management options to help informed decision making both by the forestry commission and the farmers in the wake of collaborative management concept of TROF in Ghana. Moreover, the repetitive assessment process should be easy and economically as well as ecologically sound.

Quantitative assessment of TROF in terms of volume or biomass per unit area is a useful way to provide estimates of various components that can be harvested. Assessment in terms of volume and biomass is more relevant for TROF in Ghana because the major product that is derived from the TROF is related to use of wood. For example, the main source of energy is fuelwood and charcoal (70% of the total national energy consumption is accounted for biomass where the end products are either in a form of fuelwood or charcoal, (Atakora, 1999) which is generally traded in weights, and timber, another important product, is traded in volume. Not only timber and fuelwood, but also some non timber products for example: chew sticks from Garzinia afzelii, mortars from Nauclea diderrichii, pestles from Celtis mildbraedii (Amanor, 1996) derived from TROF can be quantified meaningfully in terms of volume as well as weight because they are related to the use of wood. Other non timber products derived from the TROF mainly include the use of barks and leaves for example leaves from Newbouldia laevis and barks from Alstonia boonei (Amanor, 1996) which can also be quantified in terms of biomass. If the proportion of a particular NTFP in various parts of a tree like bark or leaf or wood is known, quantifying these tree parts in terms of biomass can help to estimate the amount of such valuable NTFPs available in the tree. Therefore, volume and biomass assessment can give the total picture of the amount of both timber and non-timber products that can be supplied from a tree, where, the conventional method of forest inventory needs separate inventories for different components for example timber, fuel wood and NTFP. Biomass estimation can also help in modelling the above ground net primary productivity of TROF which could be linked with the amount of non timber products and other nutrients present and added in the wood, leaf and bark of a particular tree species annually or periodically (Brown, et al., 1997).

To mitigate the effects of greenhouse gas emissions in the global temperature rise, more countries now seek to comply with agreements under UNFCC under clean development mechanism of Kyoto protocol which requires the estimation of carbon sequestration or release in a specific period of time. Above ground productivity derived from biomass assessment can be useful to quantify above ground carbon sequestration by the forest at any particular time interval (Brown, 1997; Garzuglia, et al., 2003). The benefit thus gained from the carbon sequestration by adoption of the 1997 Kyoto Protocol
can be an incentive to the farmers to retain the trees on their farmlands in Ghana. However, estimation of net primary productivity also needs repetitive biomass assessment.

Conventional ground based TROF assessment in terms of biomass is not as easy as the inventory inside a forest stand. It is mainly due to the scattered nature (geometry) of this resource over wider landscape, ownership of the land where the TROF is found (TROF is generally found in individual farmlands, therefore, many owners) and higher heterogeneity in terms of species composition and distribution (Kleinn, 2000). Using either biomass equations or biomass expansion factors (Brown, 1997) to assess aboveground biomass is a suitable alternative to use once they are available but preparation of these equations or the expansion factors for different forest and vegetation type in case of TROF, among other difficulties, also requires destructive sampling. Destructive sampling is not applicable in two situations. First, when estimation of single tree biomass is necessary and second when a policy or law restricts cutting down the trees for example in case where biomass of threatened or rare tree species is to be estimated. It is therefore, important that new method to assess above ground tree biomass which is not destructive is sought for.

With advent of new concepts and ideas, it has already become possible to estimate the biomass of a tree without destroying the tree itself (Montes, et al., 2000). This new concept, referred to in this thesis as “Montes method”, known as non-destructive method helps to measure a tree in a photograph using grids, rather than measuring the true tree itself. It is not possible to weigh a tree in a photograph, but the volume of different components can be estimated from it using approximations of geometric solids and corresponding diameter measurements. If the density of each tree component is known or measured, it becomes possible to estimate biomass from estimated volume without felling the tree. Since Montes method estimates biomass from the volume computed using ratio estimators, it is essential that volume be estimated precisely so that biomass per plot can be reliably estimated using the regression equations or biomass expansion factors (Garzuglia, et al., 2003). Details of this method are described in section 2.2.

With the advancements in remote sensing (higher spatial and, spectral resolution images, and different classification algorithms), it has now become possible to use these techniques to assess the TROF (Singh, 2003). Kleinn, (2000) has distinguished three levels of tasks that can be distinguished in case of TROF: land use classification and mapping, identifying the classes of tree cover (crown cover, tree density and spatial arrangement of tree crowns) and measurement of tree characteristics (stem and crown dimension, volume and biomass including non biophysical variables like ownership, management etc) and satellite imagery are suitable for the first two (Kleinn, 2000). In this context, remote sensing methods could be more suitable for the repetitive assessment of the TROF, in those two levels, because of the temporal resolution of the satellite images.

In context of TROF in Ghana, the heterogeneous landcover as shown in Figure 1.1, containing a variety of tree species (in the over storey) occurring mixed with different types of under storey landcover, often pose difficulties in classification with the pixel based classifiers (like maximum likelihood) using medium resolution satellite images i.e. the images whose spatial resolution ranges from 10 meters to 60 meters. This is because, the traditional per-pixel classification algorithms cannot disaggregate the individual materials of interest within the instantaneous field of view of the sensor system (Huguenin, et al., 1997). Moreover, the trees, due to their scattered occurrence, are generally
smaller than the spatial resolution of a medium resolution satellite sensors. This over storey landcover is again found mixed with variety of under storey landcover also later named in this document as “background material”, making the detection and the classification of over storey resource using the conventional pixel based classifiers more difficult and inaccurate. On the other hand, in medium resolution satellite images, because of the larger spatial extent (greater than a pixel), the under storey landcover can be identified with higher accuracy using the pixel based classifiers.

The occurrence of over storey tree cover affects the reflectance and hence the image classification in two ways.

a. the size of the tree crown (over storey landcover) is often smaller than the spatial resolution of the sensor, and the trees are scattered in the landscape, as a consequence the reflectance from a tree is modified by the underlying landcover within the IFOV of the sensor, resulting mixed pixels.

b. The occurrence of over storey trees also modifies the reflectance of the underlying vegetation so that even the signatures collected for under story landcover are mixed signatures (mixed pixels) and not the pure signatures.

Remote sensing image analysis typically deals with the mixed pixel problem by labelling “mixed pixels” with “mixed labels” (Huguenin, et al., 1997). A pixel containing 60% of material A and 40% of material B may be labelled as mixed AB pixel because there is no mechanism for extracting information about the proportion of individual materials of interest within pixels using traditional per-pixel classification logic. The traditional classifiers have not been successful in the identification of the proportions of several material of interest found within the IFOV of the sensor system (Huguenin, et al., 1997).

To tackle the problem of misclassification due to the occurrence of mixed pixels, two approaches that are expected to be helpful are Forest canopy density mapping and subpixel processing.

As already stated, due to the heterogeneous nature of landcover in Ghana, the spectral reflectance from the TROF is expected to be greatly modified by the underlying vegetation. However, the nature and properties of trees growing in these landcover are quite unique with regards to their size (taller than the underlying vegetation), which can at the same time be advantageous for separating them out from the underlying vegetation. Indices which can be expected to distinguish this difference are the Shadow Index (SI), Crown Cover or NDVI that can be computed using a software named Forest Canopy Density Mapper produced by Japan Overseas Forestry Consultants Association (JOFCA) (Rikimaru, et al., 1999). The details are in section 2.6.

Another approach that is expected to be helpful is subpixel processing. Subpixel processing can be defined as the search for specific materials of interest from within a pixel’s mixed multispectral image digital number spectrum. This kind of subpixel processing provides important information on the relative proportion of the material of interest found within a pixel. ERDAS Imagine subpixel classifier is one of the spectral image exploitation tool which can detect materials that occupy less than 100% of an image pixel and provides an estimate of the amount of material present in each pixel. It is expected to identify which pixels in an image contain the material of interest and reports how much of
the material of interest is present in each pixel. (Online help imagine sub pixel classification, more elaboration of the principles is in section 2.6)

These two classification algorithms can be expected to be useful in detection of the TROF in Ghana. Moreover, if any relationships between the satellites image variables and the TROF variables on the ground assessed using the non-destructive method can be established, it is expected that the amount of repetitive fieldwork that is necessary for the destructive resource inventory is reduced drastically which has direct implication on the cost and time incurred to collect the data. Therefore, a remote sensing based precise tree volume assessment method for TROF assessment is very essential.

In this research an attempt has been made to assess TROF volume as a first step in its biomass estimation using remote sensing techniques. This research focus to establish a link between the satellites based remote sensing and ground based remote sensing to estimate precisely the above ground wood volume of TROF using Montes method. The innovative part of the thesis is the improvement that is suggested in the Montes method so that errors in this method can be minimized and hence, the above ground wood volume can be precisely estimated.

1.4. Research Objectives

The objective of the research is to explore the potential of satellite remote sensing and image classification techniques, combined with ground-based non-destructive volume assessment method for quantitative assessment of the TROF volume per plot in off-forest reserve areas in Ghana.

With respect of the ground based non-destructive volume assessment method we will review the Montes method and procedure that is used in the method to estimate the volume and biomass of a single tree using an ordinary photograph, identify its shortcomings if any, and explore the possibility to improve this method so that more reliable volume/biomass equations can be prepared without felling down the trees in the field. Regression equations will then be applied to link variables per pixel derived from remotely sensed data and relate these to above ground wood volume per plot derived from non-destructive method as a primary step in estimation of above ground plot biomass (Figure 1.2). Specifically, the objectives are:

- To test whether Montes method to estimate single tree volume and biomass gives accurate estimate of the tree volume with errors within acceptable limits. If not, to improve the method and validate the proposed improvements.

- To test whether the shadow index and NDVI available for use in Forest Canopy Density Mapper (FCD Mapper) can differentiate between the over storey tree canopy and underlying vegetation and to test its findings with the results obtained from sub-pixel classification using ERDAS imagine.
1.5. Research Hypothesis

- The Montes method to estimate the single tree volume and biomass can accurately estimate the above ground wood volume of trees of different shapes and size.
- Indices used in FCD Mapper can differentiate between trees and the underlying vegetation cover in off forest reserve areas of Ghana hence, it gives higher classification accuracy as compared to the sub-pixel classifier in detecting the TROF.

1.6. Research Questions

- Does the Montes method estimate the above ground wood volume of a tree within acceptable range of error limits? if not, are there possibilities to improve it?
- With respect to classifiers, which of the two classifiers; ERDAS Imagine sub-pixel or FCD Mapper give higher classification accuracy in detecting the TROF?
- Which index among NDVI, shadow index (SI) or crown cover (CC) used in FCD Mapper or crown cover derived from sub-pixel classification will show the highest correlation with the TROF volume per plot?

1.7. Research Approach

![Figure 1.2: Conceptual framework of the research.](image)
1.8. Organization of the Thesis

Chapter 2, Methods and Materials, explains the study area in brief. It explains Montes method in detail and the different experiments setup to test this method. It also explains the basic concepts of FCD Mapper and Sub-pixel classifier and logic why and how they were used to detect and assess the TROF in off-reserve areas of Ghana. Statistical analysis used to derive regression equations are also discussed in this chapter. Materials used in the research are also tabulated.

Chapter 3, Results, deals with the outcomes of the experiments. It also explains model stem approach as a modification proposed in the Montes method, to minimize errors in computation of aboveground wood volume. It also incorporates the findings of the image analysis using subpixel classification and FCD Mapping classification algorithms.

Chapter 4, Discussion, discusses the findings in the light of methods used and the results obtained. It also discuss about the relevance of this research and the prospective users of the findings.

Chapter 5 and 6, Conclusions and Recommendations, concludes the study with the direction for future research.
2. Methods and Materials

2.1. Study Area

For the present study following setting of TROF occurring landscape was preferred
- The should be representative of the TROF in Ghana.
- The site should be easily accessible and relatively flat.
- Satellite images, maps and other data of the site should be available
- Wide range of TROF in terms of species and their occurrence in different landcover classes

The study was conducted in Goaso district in Ghana (Figure 2.1.) where above-mentioned characteristics in the landscape were found. Relatively flat area was preferred because it is difficult to take a tree photograph in a undulating terrain. Moreover, slope might also introduce photographic distortions in the tree photographs. Due to the scattered nature of the TROF in the landscape, visiting widely separated sample plots on foot was not possible given the short duration of the field work. Therefore, the site that was easily reachable by a vehicle was chosen. In addition, the study is one of the collaboration efforts between forestry commission of Ghana, TROPENBOS and ITC to investigate possible options for TROF assessment in this particular area, therefore the research results could also become relevant to these institutions. Secondary data were available and logistics arrangement was easy, that was another reason to prefer this area for the research.

The boundary of the study area (Figure-2.1) was digitized on screen using ASTER image as the base. Visual assessment of false colour composite (FCC with 321-RGB) showed that the southern part of the image was covered partially by haze, therefore this part was excluded from the study as it might have introduced error in classification of the image in later stages. A long stretch of forest reserve boundary bordering the area in the west was taken as the western boundary and major roads which could be clearly seen in the east, south and north were considered as the boundary of the study area for the purpose of this research.

Location
The area is located in south east of Goaso district in Brong Ahafo region approximately 140 km west from Kumasi, a major city centre in Ghana. It is located between 6°29’18.54”N to 6° 54’59.43”N latitude and 2° 19’54.35”W to 2° 40’15.16”W longitude and it covers an area of approximately 900sq km.

The climate in the region is hot and humid with mean annual rainfall ranging from 1500-1750 mm. Mean annual temperature varies from 26°C to 29°C. The area has two distinct seasons, a wet season which starts from May/June to October/November and a dry season starts from December/January to April/May. In the dry season no rain falls for even two to three months and most of the vegetation is devoid of leaves. The topography is gently undulating; maximum slope recorded during the fieldwork was 30 percent. The forest type found in this area is Moist Semi-deciduous, North West Subtype (Kotey, et al., 1998).
Goaso district consists of a rural community where agriculture is the mainstay of the economy. The major land use is agriculture, with cocoa being the major cash crop. Other agricultural crops include cassava, maize, plantain, cocoyam, oil palm, rice and citrus fruits but these crops are mainly for subsistence and not cultivated as the cash crop like cocoa. The farmlands in the study area are not devoid of trees. One of the major reasons of retaining trees in the farmland is for the purpose of providing shade to the remaining old variety of cocoa plantation underneath. Wide variety of trees in terms of species composition were found in the study area. (Appendix - 17) The areas presently under the old variety of cocoa farming are in the process of conversion. Farmers prefer replacing old variety of cocoa, with new improved variety of cocoa, which gives higher yields and requires less shade trees in the over storey once it is mature. In these areas, farmers practice shifting cultivation. The land that is left as fallow land are now covered with thicket of bush and grasses composed mainly of Akyeampong \((\text{Chromolaena odorata})\) and, to a lesser extent spear grass \((\text{Imperata cylindrica})\). TROF in the study area were found associated with variety of under storey landcover namely cocoa, plantain and cassava. TROF were also found considerably in fallow lands and marshy areas, and surrounding the individual homestead. Since these areas were cleared for settlements and for agriculture purpose for the last many years, the trees found off reserves were similar in species to the trees inside forest reserves. Farmers didn’t plant the trees by themselves in their farmlands therefore, no distinct configuration was observed in the study area.
2.2. Montes Method to Estimate Tree Volume and Biomass in a Non-destructive Way

The usual way to estimate above ground biomass of a group of trees or a patch of a forest is to establish equations that relate tree biomass with easily measurable tree variables like diameter at breast height (dbh) or tree height or both. This is done by measuring representative samples of trees belonging to particular population. These equations are then used to estimate the biomass that is applicable to the population from where the sample is drawn (Saint-Andre, et al., 2004). Measuring a tree to estimate its biomass is not easy and straight forward. It requires felling down of the trees; which is destructive (Cairns, et al., 2003; Saint-Andre, et al., 2004; Xiao, et al., 2004). Full tree harvest method, which uses cutting and weighing or cutting, drying and weighing of whole tree or its parts, is a straight forward procedure to estimate fresh and dry biomass. This method is time consuming, costly and above all destructive. A more efficient method for biomass estimation is tree sub sampling method (de Gier, 2003). This method doesn’t require weighing or drying and weighing the whole tree to estimate its biomass, but estimates the biomass from a small sample collected from the tree (be it wood or leaves) and weighing or drying and weighing only the sample to estimate its biomass. Though this method is efficient in terms of time and cost as compared to full tree harvest method, it is still destructive to the tree i.e. it requires felling.

Few attempts have been made to measure tree variables that lead to these equations without felling the trees (Vann, et al., 1998). One of the attempts involves measuring necessary tree variables by climbing up on the tree. But this is not a practical solution especially when the population is large with large variations among tree shapes, sizes and species. Yet another method was developed by Montes et al., (2000). This method is based on derivation of above ground tree biomass from the estimated tree volume using an ordinary photograph of a tree. This is the only method I encountered so far, that can be used to estimate the above ground biomass of each single tree without felling down the tree. Moreover, this method is more suitable to estimate the volume and biomass of tree stands in open woodlands or of isolated trees (Montes, et al., 2000) a condition that is usually found in TROF in Ghana. Therefore, it was decided to use this method in this research. Literatures suggested that this method has not been widely applied for tree biomass assessment. Therefore, testing this method was essential before it was actually used in the research.

Montes method to estimate volume and biomass of an individual tree is primarily based on measurements and calculations made on an ordinary photograph of the tree. This method was applied to estimate the volume and biomass of Juniper tree (Juniperus thurifera) in Morocco. The photographic method as explained in (Montes, et al., 2000) basically involves 6 major steps. It uses Microsoft Excel for windows for data entry (coding), an excel macros for data processing (calculations) and an excel sheet for storage of the results. Biomass of various components of a tree is estimated based on the computerized evaluation of tree bio-volume. The steps follows:

1. Photographing a tree : Two photographs of each tree from orthogonal view, physical samples of different components of tree (branches and foliage) and dendrometric measurements
2. Calculation of the scale of the photograph
3. Determination of the volume of the different components of the tree (trunk, branches and foliage)
4. Determination of bulk density of these different components
5. Calculation of biomass for the different components
6. Validation

These steps are elaborated below.

**Step 1: Photographing a tree**
The tree is photographed from two orthogonal directions. Two photographs were necessary due to axial asymmetry of *Juniperus thurifera*, the tree in which the method was used by the author to compute its volume and biomass. The cross section of this tree is often elliptic. The equation of ellipse area is $\pi ab$, where $a$ and $b$ are the half-axes. The equation of crown surface area is $\pi a^2$ under its narrow profile and $\pi b^2$ under its wide profile, for a given height. The surface area is thus the geometric mean of the two surface area = $\pi ab$, the ellipse area. The same applies to volume also.

**Step 2: Calculation of scale**
The photographs are scanned and its scale is calculated. The scale is not the simple ratio between the size of the tree in the photograph and the real size of the tree. The scale also depends upon the size of the grid cells used for data entry, and the resolution used to scan the photograph. The scale is obtained by the following equation:

$$S = \left[ \frac{D}{R/100} \right] \times \frac{C}{y}$$

Where, $S$ is the scale; $D$, Tree height in meters; $R$, Scan resolution (in dpi); $y$, tree height on the photograph (mm); and $C$ is the grid cell size (in mm).

**Step 3: Volume Calculation**
Each scanned photograph of the tree is imported into EXCEL workbook as background image. A grid of known size is superimposed on the photograph. Each square of the grid i.e. the grid cell is represented by a 'pixel', to which is attributed a code for different components of the tree. Four kinds of pixels were defined by Montes with following alphanumeric codes:

- Trunk and vertical of sub-vertical branches: Pixel B
- Trunks and horizontal or sub-horizontal branches: Pixel H
- Foliage: Pixel F
- Internal Crown: Pixel M
For the purpose of understanding, an example of coding of a trunk and horizontal branch\(^1\) is shown in Figure 2.2. Pixels corresponding to the trunk are coded as B and the horizontal branch are coded as H. These alphanumeric codes are then replaced successively by value 1, enabling calculation of the volume of the different kinds of pixels\(^2\), automated by macros in Microsoft Excel.

**Volume of the trunk (pixel B)**
For pixel B, the macros first converts every such pixel to a value 1. The macros then sums up every uninterrupted succession of pixels in a row (shown by red lines in Figure 2.2), which corresponds to the diameter (d) of the trunk. This sector is treated as circular section and is applied to the formula of cylinder volume:
\[
v = 0.25\pi d^2 h\]
where, h is the height of the grid cell which is also 1.

If there are n such rows which corresponds to the trunk of the tree, all circular sections (1 to n) are added together throughout the trunk so the volume of the trunk then becomes

\[
v = \sum_{i=1}^{n} (0.25\pi d_i^2 h_i)\]

This volume (v) after multiplying with the scale (S\(^3\), explained in step 2) will give the true volume of the trunk.

**Volume of the horizontal branch (pixel H)**
H corresponds to the wood components in horizontal or sub horizontal positions as shown in Figure 2.2. The calculation method is same as employed for pixel B, first the conversion of the code into value 1 and summing up to find out the diameter. Since the branch is tilted, the calculations are

---

\(^1\) For the purpose of this research and to understand the underlying concept of this method, only trunk and branch volume is considered in this research. Detail of the method is in Montes et al., (2000).

\(^2\) A term “face surface area” was proposed that represents the total pixel area coded either as B or H or F or M depending on which particular component of the tree the code refers to in the photograph.
carried out down the columns rather than across the row as shown in Figure 2.2. with cyan coloured lines.

**Step 4 and 5: Determination of Bulk density and biomass of each component**

The bulk density of each component is determined from the volume and oven dried mass of the samples collected from the tree in the field. The bulk density of each component is then multiplied with the volume calculated in step 3 to estimate the biomass of each component.

### 2.3. Analysis of Montes Method

Montes method to estimate the volume of a tree could become problematic when the tree or its branch tilts with respect to the grid lines. The decision to whether the diameter should be measured along the row (as shown by white lines for code B) or along the column (as shown by cyan lines for code H) as shown in Figure 2.2, is one of the major concerns because, both of which do not represent the true diameter of the trunk or the branch at that point. Another ambiguity can arise due to different codes that are supposed to be used for the trunk and the branches. If we look at the junction of the trunk and the branch in the same Figure 2.2, it is extremely difficult to decide from where the trunk ends and the branch starts.

Moreover, while deciding on whether to code a grid cell to represent a particular component (trunk or branch) or not also depends on the size of the grid cell used to code the tree in the photograph. For example, considering the grid cell in pink colour in Figure 2.2. whether this grid cell should be coded to represent the trunk or not can introduce bias. If it is decided to include this grid cell in the measurement, the diameter is overestimated, if not, the diameter is underestimated. This could therefore, introduce errors in final volume computation. It was therefore, necessary to understand the effects of the branch tilts and the grid cell size on the final volume computed using this method. Therefore, an experiment were set up to test this effect. Details follow in section 2.4.

### 2.4. Testing the non-destructive (Montes) Method

The Montes method, explained above, was first tested for its accuracy in estimating the volume. For this purpose following conceptual framework (Figure 2.3) was prepared so that this method can be tested and, if necessary, improved, before actually applied further in this research.

![Figure 2.3: The approach used to test and validate the Montes method.](image-url)

**If method is reliable**

- Understanding Montes Method
- Simulating
- Improving
- Validation
- Application

Testing the method by coding objects of known dimension and a real tree

Identifying the sources of errors and checking the possibility to minimize them to improve the method

Validating the proposed improvements (model stem method)

Applying the improved method to quantify the TOF in Ghana
2.4.1. Understanding the method through simulation

After discussion with my first supervisor, two experiments were set up to test the method. In the first experiment, it was decided to use this method to estimate the volume of a cylinder and a frustum of a truncated cone (FoC), both of known dimensions. A cylinder and a FoC were chosen for the experiment because Montes method assumes that the section of the tree trunk or a branch resembles a section of a cylinder. However, in reality the section of a tree trunk resembles more to a section of a FoC. Therefore, it was decided to use both of these objects for this experiment. The true volume of the cylinder and the FoC were computed using the formula given below.

Volume of a cylinder = \( \frac{1}{4} \pi d^2 h \) ........................................... Eq-1.

where, \( d \) is the diameter and \( h \) the height of the cylinder.

Volume of FoC = \( \frac{\pi h}{3} (R^2 + r^2 + Rr) \) ........................................... Eq-2.

where, \( R, r \) and \( h \) are the base radius, the apex radius and height of the FoC respectively.

As already stated Montes method uses the photograph of the object in question and not the object itself. Therefore, the perspective view of both of these shapes were used in the experiment (Appendix-5). The objects were coded using three different sized grid cells size namely 2mm, 3mm and 4mm (after calculating the scale for each grid cell size, Appendix 6) to understand the effect of variation in grid cell size in the calculated volume. Both of these shapes were tilted at angles ranging from 0° to 90° at an interval of 10° each with respect to vertical grid lines and the volume was computed for each tilt angle and for each grid cell size for both the cylinder and the FoC using Montes method. The error was calculated as the difference between the calculated volume and true volume of the object and expressed as the percent of the true volume. The error percent was plotted in a graph to check how the variation in tilt angle and the size of the grid cell affects the volume computed using Montes method.

2.4.2. Testing the method in a real tree

In the second experiment a real tree was used to test the method. It was necessary to use a real tree because of two reasons. The first, a tree has branches that are tilted in various directions with respect to the grid lines at a same time. To understand, whether the different coding system applied in the Montes method is easily applicable in practice or not was the main question to answer, which can’t be answered by the first experiment since the object doesn’t have any branches in it.

The second reason was, the objects used in the first experiment were not photographed by a camera but they were prepared manually to represent the perspective view of the object. To simulate the Montes method which is based on using the photograph, a real tree was used and photographed by a digital camera. This is also different from the Montes method because Montes used analog camera to photograph a tree and later scanned the photograph. Where as, I used digital camera itself so scanning was not necessary and therefore the scale calculation procedure was simplified (Appendix-6).

The volume of the real tree was estimated using the tree subsampling method as described by de Gier (de Gier, 2003). The parts of the branches below 2.5 cm diameter were ignored both in the volume estimation by subsampling method and also by the photographic method. The volume thus obtained
was the true volume of the tree under consideration. The main axis of the tree was tilted at angles ranging from 0° to 90° with respect to the vertical grid line. Each of the branches were coded separately using three different grid cells of size 2mm, 3mm and 4mm using Microsoft Excel and the volume was computed using Montes method. The error was calculated as explained in section 2.4.1 and was plotted in a graph to check its variation with the variation in tilt angle of the object and, the grid cell size used for coding.

2.5. Improvement of the Montes method

2.5.1. The hypothetical tree

Another experiment was set up to test whether the ambiguities that are present in coding the tree and its branch differently and the cumbersome method to measure the diameter of the branch and the trunk in two different directions based on the tilt angle of the branch, can be reduced and the method can be simplified. The idea behind this experiment was both the tree trunk and the branches basically is composed of wood, and we are interested in volume of the wood irrespective of whether it is in branch or the trunk irrespective of their tilt angle. Therefore, to test whether a single coding scheme can be applied for both the branch and the trunk, a hypothetical tree, of known dimension was prepared by joining perspective views of three FoC of same dimensions (Appendix 7). This composite object was assumed to represent a tree trunk with two side branches. The object was coded exactly the same way as in the first experiment using 3mm grid cell and its volume was computed using the Montes method. In the next step the trunk and the branches of the hypothetical object was given a numeric code “1” irrespective of its tilt angle. All the codes that represented the face surface area of the object were added together irrespective of whether the code represented the branch or the main trunk. A new FoC, named as “model stem”, was constructed using the grid cells of the same size that was used to code the object. In addition to it, the number of grid cells in the base diameter, apex diameter and face surface area on the true object was kept same in the model stem. Its height, the height of a trapezoid can also be precisely calculated by counting the number of grid cells that represented the height (Appendix 6 and 7) and its volume was computed using the formula to compute the volume of a FoC as mentioned in equation 2 in section 2.4.1. The volume computed using the “model stem method” was compared with the known true volume of the hypothetical tree.

2.5.2. Validation of the model stem method and its application in Ghana

The model stem method as proposed by the second experiment was tested using the same photograph of real tree in a third experimental set up. Photograph of the real tree with known volume was again coded using the numeric code “1” irrespective of whether it represented a trunk or a branch. The photograph was tilted in the different angles and coded using three grid cell sizes as mentioned in section 2.4.2. Model stem method was used to compute the volume. The error was again calculated and expressed as a percentage of the true volume and plotted in a graph as described in section 2.4.1. The error in volume of the real tree by using model stem method was compared with the error obtained by using Montes method for different tilt angles and for different grid cell size used for coding. This approach was used to compute the volume of trees that were photographed in Ghana. (Appendix- 8)
2.6. **Image Classification**

2.6.1. **Subpixel Classifier**

The subpixel process detects the material of interest (MOI) in a pixel under investigation by subtracting fractions of candidate background (BG) spectra, and then identifying the background and fractions that produces the residual spectrum that most closely matches the spectrum of material of interest. For each candidate background, residuals are computed that produce the best spectral match to the spectrum for the material of interest. (Huguenin *et al.*, 1997). This is illustrated in Figure 2.4.

![Figure 2.4: Concept of ERDAS Imagine Subpixel classification](image)

Suppose a pixel on an image is composed from the reflectance spectra from two different elements from the ground. For example, tree in the over storey with cocoa in the under storey. This research is interested in identifying the tree in the pixel, which is the material of interest, MOI. It should be separated from the reflectance contributed by cocoa that is in the under storey in the field or as the background material in the image. This classifier removes the spectra of the cocoa and yields a balance of the spectra of tree in the pixel (material of interest). It also results on how much percentage of the pixel is contributed by the tree (MOI), more specifically the crown of the tree in that pixel.

The geo-referenced ASTER image of March 2004 was used for classification using ERDAS Imagine subpixel classifier. The complete processing of an image using Erdas imagine Subpixel classification involved four major steps namely Pre-processing, Environmental correction, Signature derivation and MOI Classification. Signature can be derived either manually or automatically. The details of which can be found in online help of Erdas Imagine subpixel classification provided in the software.

The signature derived from the forest reserve was used to prepare input training set area of interest (AOI) file. The signature that were collected from the old fallow, young fallow and cocoa with trees were used to prepare input valid AOI file. The signature that was collected from the settlements and roads without trees and cocoa without trees (new variety of cocoa) was used to prepare the input false AOI file. Automatic signature derivation option was used to derive the signature. The signatures were evaluated using the signature evaluation module in this software. The signature with the least evaluation value of 0.28 was chosen as the best signature (ERDAS help file), which was used to classify the TROF in the study area. Signature evaluation report is in Appendix 9.
2.6.2. Forest Canopy Density (FCD) Mapper

As already mentioned, the occurrence of over storey vegetation, mixed in various proportions of under storey vegetation, poses difficulty in classification of the image using the conventional image classification techniques. But this kind of mix of the vegetation components in different vertical strata (Figure 1.1 and 2.5) at the same time can be advantageous to distinguish between them using another image classification technique called the Forest Canopy Density (FCD) Mapper. In Ghana, though, the spectral reflectance of the TROF is expected to be greatly modified by the underlying vegetation, the nature and properties of trees growing in these landcover are quite unique with regards to their size (taller than the underlying vegetation), which can at the same time be advantageous for separating them out from the underlying vegetation. One of the indices that could possibly distinguish this difference is the shadow index that is available in the FCD Mapper (Rikimaru, et al., 1999).

FCD Mapping and monitoring model, also called a semi-expert system, can stratify the forest into different canopy densities ranging from 0 % to 100 %. The source remote sensing data for FCD model is LANDSAT image. The FCD model comprises biophysical phenomenon modelling and analysis utilizing data derived from four indices namely: Advanced Vegetation Index (AVI), Bare Soil Index (BI), Shadow Index or Scaled Shadow Index (SI,SSI) and Thermal Index (TI) The formulae to calculate these indices are explained in Appendix 3.

The concept behind this model is that vegetation and shadow index increases with increase in tree canopy i.e. the more dense the canopy is the higher is the value of these two indices (Figure 2.5) In contrast, bare soil and thermal index decrease with increase in canopy density. The ground vegetation, which has a considerable higher vegetation index, can be separated from the tall trees as the ground vegetation has a low value of shadow index (Figure 2.5). The information about the forest canopy can thus, be derived based on the characteristics of these four indices derived from the image as shown in Table 2.1. Canopy density is expressed in percentage for each pixel, (Rikimaru, 2000), FCD Mapper version 2.0 online help)
Table 2.1: Indices used in FCD Mapper to compute canopy density

<table>
<thead>
<tr>
<th>Indices</th>
<th>HIGH FCD</th>
<th>LOW FCD</th>
<th>Grassland</th>
<th>Bareland</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVI</td>
<td>Hi</td>
<td>Mid</td>
<td>Hi</td>
<td>Low</td>
</tr>
<tr>
<td>BI</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Hi</td>
</tr>
<tr>
<td>SI</td>
<td>Hi</td>
<td>Mid</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>TI</td>
<td>Low</td>
<td>Mid</td>
<td>Mid</td>
<td>Hi</td>
</tr>
</tbody>
</table>

The Logic

Tall trees are expected to cast shadow during day time. Shade, thus provided by a tree or a group of trees on the bare soil or the vegetation underneath can therefore, modify the spectral reflectance that could be distinguished by the shadow index (Figure 2.6). If this variation is captured by the shadow index; it is possible to say that it is definitely a shadow from a tall object like trees (where tall buildings or other features are not present) so that it can help us infer about the occurrence of a tree at that location.

Figure 2.6: The concept of the Shadow Index (SI)

Figure 2.5. clearly shows two contrasting curves; namely the temperature curve and the shadow curve. If we visualize the real world with the help of the figures above (Figure 2.5 and 2.6), we can say that when there are more trees there is more shadow. As the shadow changes so does the shadow index. (The algorithm is presented in Appendix 3). It can be expected that where there are no trees (or taller vegetation like trees) shadow index should be different than the place where there are trees. Shadow index, therefore, was used to detect TROF in Ghana.

FCD Mapper version 2.0 was used to classify the Landsat ETM image of February 2002. The software has automated the process to derive the canopy cover from the ETM image but user has to provide some threshold values. Therefore, it necessitates for prior knowledge of the area in the user who is using this software to classify the image to decide for the different thresholds values. To assist the process of providing these thresholds, thematic maps and the ASTER image of the year 2004 (due to its higher resolution) of were taken into consideration. For example the drainage map was used to derive a threshold for water. Canopy density per pixel from Landsat ETM was thus, computed for the study area. The three image variables namely NDVI, SI and CC were used to derive information about the presence or absence of the TROF and quantify them in terms of volume per plot in the study area.
2.7. Sampling Design for Field Data Collection

Two-phase sampling design (de Gier, 2003) was used in this study (Kleinn, 2000). The first phase sampling unit constituted 80 pixels selected randomly (without replacement) from Landsat ETM image of February 2002. Simple random sampling was adopted in this research because no distinct stratification in terms of geometry of TROF was observed in the satellite image. A sample plot of size 30m by 30m was selected to match the pixel size of Landsat ETM image, which was used for FCD classification. This plot size had to be chosen because the primary aim of the research was focused in assessment of TROF, if smaller size of the plots, to match the pixel size of ASTER were used, due to the scattered nature of the TROF in Ghana; the possibility to encounter empty plots would have been more, which could have lead to biased conclusions. Further, the positional accuracy of the GPS receiver that was used during the fieldwork was 15 meters, that can even reach up to 100m under some special circumstances (Garmin, 1998), if small plot size were chosen; it would have introduced errors in locating the plots. 30 meters plot can accommodate 4 ASTER pixels in it therefore, even if the positional accuracy from GPS is 15 meters, it is possible to remain within the plot and collect the data. Data was collected during the month of September and October, 2004. In the first phase sampling units Crown cover (CC), NDVI and SI were derived using FCD Mapper and ILWIS from the Landsat ETM image. The centre of these same plots were also located in the ASTER image of March 2004. Sub-pixel classification of ASTER image resulted in the percent of the tree cover in each pixel including those 80 first phase sampling units. The percent of tree cover in each pixel were taken as a surrogate for canopy cover in the selected first phase sampling units.

The idea for selecting the second phase sample was to choose 25 sampling units (trees) among the 80 first phase sampling units purposively. It was done purposively because, originally this research was intended for applying the tree subsampling method for biomass estimation and validate the biomass obtained from the Montes method using the subsampling method as a reference. Subsampling method calls for destructive sampling of the trees in the field to take necessary measurements. Since it was not possible beforehand to know whether or not trees would be allowed to cut down in the pre-selected 25 among those 80 plots, it was decided to select them purposively after reaching in the field. Another important reason for selecting the second phase sampling units purposively was due to the photographic method that was used in this study. Since photographing a tree requires several conditions to be met in the sample plots for example the area should be relatively open to allow enough light in the camera reflected from the tree. One tree per plot was supposed to be selected purposively in such a way as to incorporate as far as possible all the representative diameter class and the species that were found in the study area.

However, the second phase sampling scheme had to be modified in the field a little bit, because it was not possible to cut down the trees in any of the 80 first phase sampling units. Cutting trees among other things also depended on the consent of the owner as well as on the availability of the chain saw. Therefore, I had to follow the timber concessionaire who was carrying out the felling in the area. Moreover, the size of the chain saw put the limitation on the size of the tree that was cut down and the farmers as well as the timber concessionaire’s preference on the tree species put the limitation on the species selection. The felling was mainly concentrated in the southern part, in the area where the timber felling operation was going on. However, care was taken that the selected trees were located at considerable distance from each other and were able to meet the criteria listed above. The plots where
the second phase sampling units (trees) were felled were named differently as prefixed by $S$ shown in
Figure 3.8. Therefore, from the original 80 first phase sampling units only 55 were actually visited for
data collection and the rest 25, selected purposively, were incorporated in the first phase sampling
units. Thus, there were still 80 (55+25) plots in total comprising the first phase sampling units out of
which 25 were included in the second phase (Figure 3.5).

In the first phase sampling units (55+25), variables listed in the Table 2.2 were measured in the field.
In each plot, all the living trees with dbh more than 10cm were measured. Three dominant trees height
in each plot were recorded. The tree crown cover in each plot was estimated using optical densiometer
wherever it was applicable. In plots where a dense under storey vegetation impeded the visibility of
the over storey trees making it impossible to use the densiometer, crown cover per plot had to be
estimated using ocular estimation. In addition to 80 plots mentioned above, location information of
different landcover were collected using the GPS among which 8 points were from the forest reserve.
The purpose of these points was to serve as a training set for different land cover types. Points inside
the forest reserve was collected for the pure spectral signature of trees.

Table 2.2: Variables measured in the field

<table>
<thead>
<tr>
<th>S.N</th>
<th>Variables</th>
<th>Description</th>
<th>Instrument/software</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coordinates and Altitude</td>
<td>X and Y location of centre of the plot</td>
<td>Garmin 12 XLS GPS receiver</td>
</tr>
<tr>
<td>2</td>
<td>Tree Diameter over bark</td>
<td>Diameter at breast height &gt;10cm</td>
<td>Diameter tape and Calliper</td>
</tr>
<tr>
<td>3</td>
<td>Tree Height</td>
<td>Height/length* of the tree</td>
<td>Haga altimeter and Tape*</td>
</tr>
<tr>
<td>4</td>
<td>Canopy Cover</td>
<td>Tree Canopy in the plot</td>
<td>Densiometer, Ocular estimation</td>
</tr>
<tr>
<td>5</td>
<td>Bearing and distance</td>
<td>Navigation where GPS has poor signal receive due to thick over story cover</td>
<td>Suunto compass and measuring tape</td>
</tr>
<tr>
<td>6</td>
<td>Slope</td>
<td>Slope of the plot</td>
<td>Clinometer</td>
</tr>
<tr>
<td>7</td>
<td>Photographs*</td>
<td>Photographs of 31 trees</td>
<td>Digital Camera/Adobe Photoshop</td>
</tr>
<tr>
<td>8</td>
<td>Tree fresh wood biomass*</td>
<td>31 trees wet wood biomass estimated by subsampling method</td>
<td>Tree subsampling program with hp LX200 handheld computer</td>
</tr>
<tr>
<td>9</td>
<td>Wood sample wet weight*</td>
<td>Wet weight of the wood sample collected in the field using subsampling method</td>
<td>A battery operated electronic weighing scale with accuracy up to a gram</td>
</tr>
</tbody>
</table>

*Measurements made in the second phase sampling units.*

A single tree (second phase sampling unit), selected purposively in each of the 25 plots mentioned
above, was photographed for its volume estimation using model stem method. A total of 31 trees were
photographed in selected 25 first phase sampling units. It was because in one of the plots, the tree was
forked below the dbh and of the remaining 24 plots, two trees were photographed in four plots and
three trees were photographed in one plot. The trees after photographing were felled and its height
was measured using a measuring tape. Above ground wet wood biomass of these felled trees up to minimum branch diameter of 2.5 cm was estimated using tree subsampling method in the field using a handheld computer (hp LX200). Two wood samples were collected from each tree stem whose location was determined by the sub sampling program. The samples were collected to determine the dry density of the wood and later on to estimate the dry biomass of the tree.

2.8. Data Analysis to derive plot volume from dbh, and its relation with crown cover, NDVI and Shadow Index (SI)

2.8.1. Analysis of the data obtained from second phase sample units

The dbh of the 31 trees obtained from 25 plots were used to prepare the volume equation of individual trees. Above ground wood volume of each tree (dependent variable) was computed from the photograph using the model stem method. The estimation of the volume was restricted up to the crown height of the tree because it was not possible to see the branches due to the dense foliage during the season when the photographs were taken. The dependent variable was then related to tree dbh (independent variable) using regression technique. Residual plots (Figure 8.5 Appendix 12) revealed that the assumption of the linear model for regression that the variance of the response variable is constant was not followed. The standard technique to stabilize this variance in the dependent variable by using weighting. Using a third degree polynomial with background elimination to retain the significant coefficients, combined with weighing to obtain constant residual variance can eliminate the problem of non-constant variance of the response variable (de Gier, 2003) Therefore, weighted linear regression was used where weight equivalent to \((1/\text{dbh}^{1.8})^2\) was used in dependent variable. Constant residuals was obtained after applying the weights (Figure 8.6 Appendix 12).

The above ground wood volume per plot for all the first phase sampling units after removing the outliers, was estimated using this equation derived by weighted linear regression from the first phase sample plots.

2.8.2. Analysis of the data obtained from first phase sample units

Independent variables from the first phase sampling units namely, crown cover measured in the field, crown cover derived from Landsat ETM and ASTER images, NDVI and SI derived from Landsat ETM were then tested for a relationship with the plot volume derived from the second phase sampling units using regression equations. However, the data collected from the first phase sampling units showed that the input in dbh values to prepare the volume equation ranged from 12 cm to maximum of 91 cm. However in the second phase sample units, among the 80 plots, 11 plots had occurrence of trees having diameter more than 91 cm. Since this volume equation can’t be extrapolated beyond the range of dbh used as input to prepare the equation, the plot volume calculated using this equation where the dbh exceeded this maximum diameter were treated as outliers. Of the 11 such outliers identified, Systat Software, was able to detect 7 of them based on the statistics called Studentized residual. (Appendix 10). These 11 plots (outliers) were not considered when deriving a relationship between image variables and the plot volume. The stepwise forward selection was used in the regression analysis between the plot volume (dependent variable) with the indices (independent variable) derived from the images.
2.9. Accuracy Assessment

Accuracy of the map derived after classifying using FCD mapper was calculated based on its correlation with the field measured crown cover (Kandel, 2004). Whereas accuracy of the map derived from the Subpixel classification was assessed in two ways. One way was by using the simple percentage, i.e. how many of the 80 sample plots were correctly detected for the presence or absence of TROF. And secondly, whether those detected were in agreement with what was found in the field in terms of canopy cover. This was assessed using the correlation between the subpixel derived crown cover and field measured crown cover. Since, image classification was dealing with only one class of object, which is the TROF, assessment of accuracy using confusion matrix was not relevant.

2.10. Problems encountered during the research

All the maps presented in this thesis have the map datum of Ghana given in Appendix 13. The datum was not available in the GPS that was used in the field. Therefore, during fieldwork, WGS 84 and hddd mm ss.s was used to record the coordinates. These coordinates were later converted into datum of Ghana using the transform coordinate function available in ILWIS 3.2. The accuracy of the coordinates recorded in that format by GPS receiver was checked in the field using the IPAQ, which had the correct datum in it. It was found that the coordinates recorded by the GPS were consistent to the readings available in the IPAQ.

Problems with photographing trees in the study area and the subsampling data

A complete tree could not be photographed in a single snap. This was because of the presence of tall undercover of bush and grasses in the study area. The visibility of the base of the tree was impaired once one moves away from the tree. Therefore, it was decided to take the photograph from nearby distance, so a constant distance of 15 meter was maintained to snap a tree. Depending on the height of the tree, it was shot either in two, three or four snaps. Each photograph had an overlap with the adjacent photograph with distinguishing features in each photo, which was later used to mosaic the photos together using Adobe Photoshop. (Appendix 16). In the field the tree was also felled to estimate its biomass using the subsampling method. During this process the height of the tree was measured as accurately as possible using a tape so that it can later help to compute the scale of the photograph.

Montes method suggests that a tree be photographed from two orthogonal directions to address the problem of axial asymmetry of the tree branches and crown. However, in the off-reserve areas in Ghana, due to the presence of thick bush, grass cover and cocoa, it was not possible to take photos from orthogonal sides. Almost all the trees were in the farmers’ field and farmers didn’t allow removing cocoa from two directions to photograph the tree. Moreover, the time and the labour taken to clear the bush and grass cover in both sides were huge, hence it was decided to take the photograph from only one direction.

The season when the field work was conducted was the late growing season of the trees and the agricultural crop. The trees in the area were full of green leaves in it. The branches of the trees were not visible in the photograph. Therefore, from the photographs only the volume up to the crown height (the height from where the main crown starts) could be computed. The visible branches that were
below the main crown of the tree were coded. Therefore, the aboveground wood volume here refers to the wood volume up to the main crown height of the tree.

Data of the above ground wood biomass of the trees estimated using subsampling method was stored in a the same handheld computer (hp LX200). However, on reaching to the Netherlands the subsampling data stored in the handheld computer was no longer retrievable. These data were lost. Therefore, the above ground volume and biomass derived from the photographic method could not be validated. In fact, the biomass assessment became irrelevant.
3. Results

3.1. Testing the non-destructive (Montes) method

3.1.1. Understanding the method through simulation

The first experiment (section 2.4.1) was mainly concerned with understanding the Montes method and using the method to test the accuracy in estimated volume of the cylinder and the FoC. The objects were tilted in angles ranging from 0° to 90° with respect to the vertical grid lines and the volume of each object was calculated using three different grid cells sizes namely 2mm, 3mm and 4mm. The error in estimated volume was expressed as error percent, as explained in section 2.4.1. The error percent for each tilt angle was plotted in the graph with tilt angle on the X-axis (Figure 3.1 and 3.2). The curves (Figure 3.1 and 3.2) showed that irrespective of the shape of the object and the size of the grid cells used to code the photograph, error increased with increase in tilt angle from 0° to 45°. Further increase in the tilt angle beyond 45° reduced the error again. The reduction trend continued until tilt angle reached 90°.

![Figure 3.1: Variation in the error due to change in tilt angle and grid cell size for a FoC using Montes method](image-url)
In case of the FoC (Figure-3.1), when the smallest grid cell of size 2mm was used to code the photograph, the magnitude of error varied from almost 0% at 0° tilt to as much as 16% at 45° tilt angle (Appendix 5). On increasing the size of the grid cells to 4mm the error was almost 5% for 0° to as much as 25% for 45° tilt.

In case of cylinder similar trend in the error variation was observed when the tilt angle was increased from 0° to 90° (Figure-3.2). However, when the grid cell size to code the photograph was increased from 2mm to 4mm, for 0° tilt angle it was found that the error percent remained exactly the same.

Distribution of the error resembled a bell shaped curve which was symmetric on its axis when tilt angle was 45°. It was found that the orientation of the object with respect to grid cells was symmetric when tilt angle was increased beyond 45°. Due to this symmetric orientation of the object with respect to grid cells, the diameter of the object, when it was tilted beyond 45°, was measured along the column of the grid cells (Appendix -18). Therefore, the error values were also symmetric with increase in the tilt angle beyond 45°.

### 3.1.2. The experiment using a real tree

The volume of the tree was also computed by using Montes method (Table 3.1) for different tilt angles and using three different grid cell sizes as mentioned in section 2.4.2. The true volume was estimated using the subsampling method The tilt angle was measured taking into consideration the main axis of the tree and was measured with respect to vertical grid lines. The error in this case (Appendix-8) also followed the similar pattern as that of the error in truncated cone and the cylinder. (Figure 3.3). However it was found that even when the tilt angle of the main axis of the tree was 0°,
the error was as high as 10% for the smallest grid cell of size 2mm, which was more than the error computed for the cylinder or the FoC for that angle of tilt. With the increase in tilt angle from 0° to 45° the error increased as much as 45% of the true volume. The error also increased with increase in the grid cell size from 2mm to 4mm.

Table 3.1: Volume of the real tree computed using Montes method

<table>
<thead>
<tr>
<th>Tilt angle in degrees</th>
<th>Grid cell size</th>
<th>2mm</th>
<th>3mm</th>
<th>4mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0105</td>
<td>0.0112</td>
<td>0.0113</td>
<td></td>
</tr>
<tr>
<td>22.5</td>
<td>0.0110</td>
<td>0.0118</td>
<td>0.0120</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>0.0142</td>
<td>0.0147</td>
<td>0.0147</td>
<td></td>
</tr>
<tr>
<td>67.5</td>
<td>0.0110</td>
<td>0.0118</td>
<td>0.0120</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>0.0105</td>
<td>0.0112</td>
<td>0.0113</td>
<td></td>
</tr>
</tbody>
</table>

True Volume of the tree = 0.0097, Volume is expressed in cubic meters rounded to 4 decimal places

The gaps between each of the three error curves corresponding to 2mm (pink), 3mm (blue) and 4mm (yellow) grid cells (Figure 3.1, 3.2 and 3.3) represented the difference in the magnitude of the error with change in the size of grid cell used to code the photograph.
In summary the first experiment showed that:

- In all three cases, the error in the volume computed by Montes method increased with increase in the tilt angle of the object from 0° to 45° with respect to the vertical grid lines, after which the error started decreasing again until 90° tilt was reached so the distribution of error was symmetric to 45° tilt angle.

- The error in the volume computed by Montes method increased with increasing the grid cell size used to code the object in the photograph. The error values on an average increased as much as 3.7 times when the grid cell size used to code the photograph was doubled from 2mm to 4mm in case of FoC. In case of a cylinder this increase was 2.45 times.

- The small amount of error (e) introduced in the diameter measurement due to variation in tilt of the object with respect to grid lines or the change in the grid cell size to code introduced a huge error in final volume computation given by an amount \( E = K(De + \frac{1}{2}e^2) \). Where D is the true diameter of the object in concern. (Appendix -19)

There results clearly showed that the Montes method has an important shortcoming when the object does not align properly with the grid lines the volume tended to overestimated. Because this is a situation that will occur frequently in practice, this method needs to be modified before applying it in this research. To test what kind of modification was necessary two other experiments were set up as explained in section 2.5.

3.1.3. Improvement in the Montes method

From the first experiment i.e. coding the true geometric shape objects, it was observed that when the object (here the frustum of truncated cone, FoC) tilts in different angles with respect to the grid lines, the assumed diameter of the FoC (diameter derived by the Montes method) which is either measured along the row or along the column of the grid lines, varies depending on variation in the angle at which the FoC is tilted (Figure 3.4.)

![Figure 3.4: The maximum diameter of the object when it is tilted at 10° and at 45° is shown by the thick black line](image)
Figure 3.4 shows that with the increase in tilt angle the diameter tends to increase (shown by the thick black line). As stated in section 3.1.2 a small error in diameter measurement can lead to huge errors in the final calculated volume. However, a closer look at the Figure 3.2. again shows that despite the tilt angle, the number of grid cells that are contained within the boundary (face surface area) of each of the above two truncated cones remain more or less the same. In principle, it should exactly be the same, but due to the border line cases few grid cells may increase or decrease. A little bit of discussion between my supervisor and myself led to a conclusion that: instead of measuring the diameter along the row or along the column as proposed in Montes method, we can virtually realign the truncated cone in such a way that it aligns properly with the grid lines (Figure 3.5). If this is done, no matter in which angle the object tilts (Figure 3.4), it can be realigned to represent a “virtual cone” which has the same base and apex diameter and the number of grid cells in the face surface area as that of the original object. The virtual cone in Figure 3.5 thus, can represent each of the two cones in Figure 3.4 irrespective of their tilt angles because both of the cones have the same dimension. If we compute the volume not based on the Montes method but using the volume formula of truncated cone, no matter at what angle the object tilts its volume as represented by the “virtual cone” should always remain the same. Therefore, the volume of the virtual cone should actually be equivalent to the volume of the tilted cone. This was the basic idea behind the improvement suggested in the Montes method.

Figure 3.5: Virtually realigned cone or a model cone.

To test whether the virtual cone concept actually holds true of not, a second experiment was set up. For this experiment a hypothetical tree with a main trunk and two side branches (Appendix -7) was constructed by joining three FoC of the same size as explained in section 2.5.1. This hypothetical tree was coded as explained in the Montes method, section 2.2. The volume was computed using the method. In the second stage, the hypothetical tree was coded with the same numerical code “1” irrespective of whether the grid cell represented the trunk or the branches. All the codes that represented the face surface area (section 2.2.) were summed up. Now the “virtual cone” cone, named as “model stem”, (Figure 8.4. Appendix-7) was constructed with the same number of grid cells to represent the base diameter, apex diameter and the face surface area as that of the original object as explained above. The true volume of the composite object was three times the true volume of an individual cone. Which was calculated to be 131.94 cubic centimetres (cu cm). (Details of the calculation is in Appendix-7). When Montes method was used to compute the volume of the hypothetical tree, it was found that the volume for the main trunk and the branches totalled to 138.055
cu cm, i.e. the volume was overestimated by 6.11 cu cm with an error percent of 4.63%. The volume was also computed with the model stem approach using the volume formula of the frustum of cone (eq 2 section 2.4.1). The resulting volume computed using the model stem method was 131.95 cu cm. i.e. the error was as low as 0.01%. It thus, showed that the virtual cone prepared in that way can represent the volume of the complex object composed of different cones tilted in different directions, which means that original idea of the virtual cone was true. Therefore, the volume represented by the simple model stem which can be calculated very easily is equivalent to the volume represented by a complex object with many branches tilted in many different directions. The results however needed to be validated.

### 3.1.4. Validation of the model stem method

The volume of the real tree was computed by model stem method for validation purpose. The volume such computed for three different size of grid cells namely 2mm, 3mm and 4mm and for different tilt angles ranging from 0° to 90° along with its true volume estimated using subsampling method is shown in table 3.2

<table>
<thead>
<tr>
<th>Tilt angle in degrees</th>
<th>Grid cell size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2mm</td>
</tr>
<tr>
<td>0</td>
<td>0.0098</td>
</tr>
<tr>
<td>22.5</td>
<td>0.0099</td>
</tr>
<tr>
<td>45</td>
<td>0.0100</td>
</tr>
<tr>
<td>67.5</td>
<td>0.0099</td>
</tr>
<tr>
<td>90</td>
<td>0.0098</td>
</tr>
</tbody>
</table>

True Volume of the tree = 0.0097, Volume is expressed in cubic meters rounded to 4 decimal places

The error in volume computation by model stem method using the real tree also followed the similar trend as that of the error that occurred in volume computation using the Montes method (Figure 3.6).
However, magnitude of the error was found much lower than that computed using Montes method. With the tilt angle of the real tree branch at 0° with respect to the vertical grid lines the error percent was as low as 1% for the smallest grid cell size of 2mm. With the increase in tilt angle from 0° to 45° the error increased but again the maximum error (i.e. for 45° tilt angle or the peak angle) was also as low as 2.5%. The error increased with increase in the grid cell size as in the previous method. Here again, the maximum error obtained using the largest grid cell size of 4mm was as low as 5%. The low error percent in the computed volume suggests that the volume computed by the model stem method is equivalent to the true volume of the tree under consideration.

### 3.2. Detection of TROF using FCD Mapper

Classification of the Landsat ETM image using FCD Mapper yielded the canopy density map (Figure 3.8) of the study area. The map shows the canopy cover in each pixel expressed as percentage of the total area of the pixel. The canopy cover was expressed at the interval of 10 percent each as shown in the legend. The term bareland in the legend refers to bare soils, roads and settlements/villages. It was not possible to get the values of NDVI and Shadow Index directly using this software. Therefore, the algorithms used to calculate the shadow index and NDVI in FCD Mapper were used in ILWIS 3.2 to derive shadow index and NDVI values for each pixel.
The relationship of both SI and NDVI derived from Landsat ETM image using FCD Mapper with the crown cover (CC) measured in the field gave very poor correlation coefficient (R) of -0.015 and -0.117 respectively. The scatter diagram also, (Figure 3.7) didn’t show any kind of relationship between these image variables with the field measured forest canopy density, therefore, they were not considered further in this research.

Figure 3.7: Scatter plot showing the shadow index and NDVI (per pixel derived from Landsat ETM image) with crown cover that was measured in 30 m square plot in the field
Figure 3.8: FCD Map derived from Landsat ETM image of February 2002.
The points numbered S-1 to S-25 in the south west of the map are the location of second phase sampling units, where trees were photographed and felled for the field data collection.
The correlation coefficient of canopy cover percentage computed by FCD Mapper and the canopy cover measured in the field was found higher \( R = 0.473 \) (Figure 3.9) as compared to the correlation between the canopy cover with NDVI or SI. However, the crown cover derived using FCD mapper also could not explain more than 22 percent of the variation found in the field. Therefore, it was also not considered further for analysis.

![Crown Cover by FCD Mapper](image)

**Figure 3.9: Comparison of FCD Crown cover to the CC measured in the field**

### 3.3. Detection of TROF by Erdas Imagine Subpixel Classifier

Classification of ASTER image of the year 2004 March using Imagine subpixel classifier also yielded the canopy cover map of the study area (Figure 3.10). However, Imagine subpixel classifier could detect MOI which covers at least 20 percent of the pixel only; unlike the FCD which can classify the image from 0 percent canopy cover to 100 percent canopy cover. Therefore, the areas that are represented in white are either settlement areas, bare soil, roads or those areas which have less than 20 percent tree crown cover.
Figure 3.10: FCD Map derived from ASTER image of March 2004.

The points numbered S-1 to S-25 in the south west of the map are the location of second phase sampling units, where trees were photographed and felled for the field data collection.
The correlation coefficient of canopy cover percentage computed by Erdas Imagine subpixel classifier and the canopy cover measured in the field was found higher $R = 0.846$ (Figure 3.11) as compared to the correlation coefficient between the canopy cover from FCD Mapper. Therefore, canopy cover derived from subpixel classifier was used for further relationship derivation in this research.

![Crown Cover by Imagine Sub-pixel Classifier](image)

**Figure 3.11: Comparison of CC derived from Sub-pixel classifier to the CC measured in the field**

### 3.3.1. Accuracy of Image Classification

Subpixel classification using ASTER image gave higher accuracy both in detection and in quantitative assessment of TROF in terms of crown cover. Out of 80 sample plots only 13 were misclassified. Percent of correctly classified pixels was 85% in the detection of the presence or absence of TROF in the study area. However, the accuracy dropped to 71% when it came to quantify the TROF in terms of its crown cover per pixel. (Figure 3.11)

<table>
<thead>
<tr>
<th>Description</th>
<th>Number of Pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of plots taken during the study</td>
<td>80</td>
</tr>
<tr>
<td>Number of cases that were correctly classified</td>
<td>68</td>
</tr>
<tr>
<td>Number of cases that were wrongly classified</td>
<td>13</td>
</tr>
<tr>
<td>Accuracy of the classification (%) (percent of agreement)</td>
<td>85.00</td>
</tr>
</tbody>
</table>

The accuracy of the TROF cover map derived using FCD Mapper was assessed by comparing it with the crown cover that was measured in the ground (Figure 3.9). The coefficient of determination was only 0.22.
3.4. Relationship between DBH and volume of a tree from photograph

The above ground wood volume derived from the photographic method using the model stem approach was related with the dbh measured in 31 trees to derive a volume equation. This was done using weighted linear regression technique. Weighted linear regression analysis using backward elimination technique showed that in the presence of third degree polynomial the second degree and the first degree polynomial were not significant at \( p = 0.05 \) (Appendix 4). Weighted linear regression also removed the effect due to the valley shaped curve phenomenon in the bottom left portion of the regression curve derived by using linear regression techniques using 2nd degree polynomial. Figure 3.12. and 3.13.

Figure 3.12: Regression curve derived using linear regression using 2nd degree polynomial without applying the weights. Notice the curve turning up between the DBH 10 and 20 cm.

Figure 3.13: Weighted 3rd degree polynomial with backward elimination. Notice the change in behaviour of the curve between the DBH 10 and 20 cm.
**Volume (Y) = B_0 + B_1*(dbh)^3**

- $B_0 = 9.1748300540E-02$
- $B_1 = 1.3161790630E-05$
- $R^2 = 0.87$

This equation relating the above ground wood volume with the tree dbh was used to estimate the volume of all the trees occurring in the first phase sample plots after removing the outliers.

### 3.5. Relationship between CC and Plot Volume

The stepwise forward selection in regression analysis between the plot volume (dependent variable) with the crown cover measured from the field and crown cover derived using subpixel classification, showed that the relationship between the volume per plot with crown cover per plot and crown cover per pixel was linear and the second and third degree polynomial were insignificant at $p \geq 0.05$. (Appendix - 11)

Results so far showed an increase in above ground wood volume per plot with increase in plot crown cover measured in the field (coefficient of determination $R^2 = 0.51$ significant at 0.05) Figure 3.14. This in fact implies that information about the wood volume per plot can be derived from the satellite images from which crown cover can be easily estimated.

![Plot volume vs Crown cover measured in the field](image)

**Figure 3.14. Plot Volume with crown cover measured in the field**

The relationship between crown cover measured in the field and the crown cover derived from FCD Mapper using Landsat ETM image was not satisfactory (Figure 3.9) but at the same time, crown cover values derived by subpixel classification using ASTER image showed higher correlation with the crown cover measured in the field (Figure 3.11.). Therefore, to derive further relationships of crown cover derived using remote sensing techniques, with the plot volume ASTER image was used. Results showed coefficient of determination $R^2 = 0.30$ (significant at $p = 0.05$) between above ground plot volume and the crown cover derived by subpixel classification from ASTER image (Figure 3.15).
Figure 3.15: Plot Volume with crown cover derived form ASTER image using Subpixel Classification

\[ y = 0.052x + 0.3565 \]

\[ R^2 = 0.3028 \]
4. Discussion

4.1. The non-destructive (Montes) method of volume and biomass estimation

The results presented in this study showed that the volume estimated by using the Montes method depended on among other things, the orientation of the object with respect to the grid lines. The error in computed volume using this method increased with increase in tilt angle from 0° to 45°. Due to the symmetric orientation of the object with respect to square grid cells, further increase in tilt angles beyond 45° with respect to the vertical grid lines, leads to decrease in the error again. It was because beyond 45°, tilt the direction for the measurement of the diameter also changed.

The volume estimated using the existing method also depended upon the size of the grid cells that were used to code the photograph. In general, the experiments showed that the magnitude of error was more when the grid cell size was increased. However, here it was again interesting to note that in the small tilt angles of 0° and 10°, the magnitude of error calculated for the cylinder was less for higher grid cell size of 4mm than for the grid cell size of 3mm. The curves in Figure 3.2 also showed that the magnitude of error was exactly 0 when the tilt angle was 0° or 90° for both 2mm and 4mm grid cells. This anomaly in error was due to the shape of the cylinder as can be seen in a perspective view of the photograph (Appendix 5). A cylinder when photographed looks like a rectangle in two dimensions. Therefore, the grid cells that are used to code the photograph tend to align perfectly with all four sides of the rectangular object therefore, nullifying the effect of borderline grid cells. When the grid cell size was doubled from 2mm to 4mm again the grid cells fitted within the cylinder perfectly, again nullifying the effect of borderline grid cells. This was the reason why the error was exactly 0 percent at 0° or 90° for both 2mm and 4mm grid cell size. Therefore, the shape of the object also plays a major role on the accuracy of its volume estimation.

It can also be inferred from the results of the first experiment that, the error in final volume computed using this method also depended on the number of the branches and their respective tilts. When we compare the error percent obtained for 0° tilt angle for all the three objects, the FoC, cylinder and the real tree branch, it was observed that the error percent was highest in the case of the real tree branch. It is interesting here to note that both the cylinder and FoC had no branches in their sides. Therefore, it can also be said that as there are larger variations in the number of branches and their respective tilts, even at 0° tilt angle the magnitude of error could vary. However, this needs to be verified by further research.

4.2. The model stem method

The model stem method is a valid method because the volume estimated by the model stem was found equivalent to the true volume of the object (error was as low as 1%). Besides, this method is much easier to use and much more effective than the Montes method to compute the volume. It is easy because it eliminates the problem of counting the number of grids in two different directions to determine the diameter which was necessary in the Montes method. It therefore, eliminates the need for coding the trunk and branches separately. This reduces a lot of work and of course errors that may
occur when coding the joints where branches meet the trunk because at joints of the branches and the
trunk, it becomes extremely difficult to decide where exactly does a trunk end and the branch starts.
This ambiguity in the Montes method could introduce personal bias in volume estimation. The model
stem method aggregates all the grid cells that are coded irrespective of whether the codes represent a
branch or a trunk, and prepares a model stem without any branches. Thus, the ambiguity of coding in
the Montes method does not exist any more.

Besides being easy, the model stem method is also more accurate. Figure 3.6 showed the comparison
between the error associated with the Montes method and the model stem method. The curves clearly
show the decrease in error in final volume by as much as 10 times using the model stem approach, for
the maximum tilt angle of 45°. Moreover, the model stem approach doesn’t make assumption that the
section of a tree trunk or branch resembles the section of a cylinder. It assumes that the section of the
tree trunk resembles the FoC which is more realistic. The model stem approach therefore, is better
than the Montes approach to compute the volume.

This non-destructive approach of estimation of above ground wood volume and subsequently the
biomass is quite readily applicable in the context of TROF in general and in Ghana in particular
because, this method is quick and easy to operate, cheap to adopt and most importantly non-
destructive. With the start of collaborative forest management strategy in Ghana this concept could
help the forestry commission to develop a mechanism by which atmospheric carbon sequestration by
the aboveground woody biomass in TROF can be repetitively assessed with cheap cost and without
the need for higher level technician to carry out the job. Since this method is very easy, even people
without high education or training can easily understand and adopt this method to assess their tree
resources in terms of volume and biomass. Once the biomass is known, the carbon emission or
absorption by that tree or a group of trees can be meaningfully estimated. Forestry commission can
then start the process to qualify these communities to gain benefit from the clean development
mechanism of the Kyoto protocol. The benefit thus gained from the carbon sequestration by adoption
of the Kyoto Protocol can be an incentive to the farmers to retain the trees on their farmlands in
Ghana. As already mentioned, retaining of the trees in farmland is vital for the sustainability of the
timber production from the forest reserves.

The model stem approach however, was tested using only one tree. Though this method seems
promising and theoretically correct, more validation experiments needs to be conducted. Here it must
also be considered that the error that may occur due to photographic distortions has not been taken
into consideration in these experiments. Since same photograph was used in both of the methods to
compute the volume, the error due to photographic distortion was same and hence were not significant
in these experiments. But when this method is used in a real world situation photographic distortions
(due to the variation in distance between the object and the camera as well as the tilt angles of the
camera) may play a major role in accuracy of the volume computed. However, it could not be tested
in this research due to the loss of the subsampling data.

The non destructive method though sounding promising can easily overestimate the tree volume, for
example in cases when a tree is hollow and when a tree has a buttress (Appendix - 14) During the
study many trees with hollow trunks were encountered in the area where the felling operation was
going on. Buttresses are again a common feature of many tree species in tropics. When using this method utmost care should be taken into account about the form of the tree also.

The biomass that is derived from the non-destructive approach by multiplying the wood volume with the wood density can be questionable. Density of the wood in a tree varies depending on which part of the tree the wood belongs to for example the density decreases from base to tip of stem and also the density of wood in cross section of stems tends to increase from the pith to the cambium. Also density can vary within individual annual rings (Husch, et al., 2003). This variation in wood density can lead to errors in biomass values that is derived from ratio of the tree volume and wood density. Therefore, the biomass values obtained using this method should be treated cautiously taking this issue into consideration.

However, to make this promising method operational, the issues raised above must be tackled and their effect on the computed volume and biomass must be understood properly. The most important issues that can have a serious effect on the computed volume and biomass that should be understood by further research include:

a. photographic distortions,
b. scale variations due to change in distance between the object and the camera, and
c. the non constant values of the wood density in a same tree and its effect on the biomass estimated using the ratio estimators.

4.3. Detection of the TROF by FCD Mapper and Subpixel Classifier

FCD Mapper did not give satisfactory results in detecting and quantifying the TROF. There could be various reasons for this. The first is, the image that was used for FCD mapping purpose was too old, 2002 February where as the field work was conducted in October 2004. The TROF resource in Ghana are depleting at a faster rate (Kotey, et al., 1998). Even during the field work the sound of the chainsaw from the off reserve areas was very prominent every day. Therefore, it is logical to say that a lot of change in the tree cover has probably taken place in this area since 2002 February. Figure 4.1 clearly shows the amount of reduction in canopy cover between March 2004, derived from ASTER image and October 2004 the time when the data was collected from the field work. If we look at the trend of canopy cover reduction in this interval, the canopy cover map that was derived from by FCD Mapper also looks realistic. This change in canopy cover could be one of the prime reasons for low correlation between the crown cover measured from the field and that derived from FCD Mapper.

Another cause that has probably affected the correlation between the crown cover measured in the field and derived from the FCD mapper could be the difference in season of image data and field data collection. The image was collected in February, which is the dry season in Ghana. In dry seasons, the tree are mostly devoid of leaves (the forest type of the study area is also moist deciduous). The leaves are those tree components which contribute more to the reflectance from the tree canopy than the branches devoid of leaves. Moreover, field work was conducted towards the end of the rainy season, when all the vegetation was full of green leaves. These leaves in turn played major role in estimation of the crown cover during field work. This mismatch due to the seasonal variation could be another important reason for the low correlation between the CC derived from FCD Mapper and the field data. This explanation also holds true for the poor correlation between the NDVI and the crown cover.
Another reason that has influenced for the relationship between the crown cover measured in the field and that estimated using FCD Mapper and Subpixel classifier is due to deliberate killing of the trees with ring barking and burning, which framers practice in that area to get rid of the trees from their farmland. During the field work it was found that out of 80 plots 33 plots had the occurrence of dead trees. Out of the 33 occurrence 11 were found to be dead due to natural death and the rest 22 were due to deliberate killing by the farmers (Appendix – 14).

The ratio of the dead tree to live tree was 0.30, which is quite high. This also justifies for the change in crown cover that would have occurred during the past two years between February 2002 and October 2004. Moreover, the instrument used to estimate crown cover was the optical densiometer, which was not readily applicable in two storey vegetation cover like that of the study area. Therefore, in many circumstances ocular estimation of the canopy cover had to be made, which could have introduced bias.

The concept of shadow index didn’t work at all in detecting the TROF as previously hypothesised in this research. One of the prime reasons is again due to the season of image data collection because, the trees which are devoid of leaves in their crowns do not produce substantial amount of shadow for a medium resolution satellite sensor like Landsat to detect.

Subpixel classification gave higher accuracy in both detection and quantitative assessment of the TROF i.e. the relationship between the CC and the plot volume. This could partly be due to the inherent algorithms that is used in this classification technique itself, partly also because of higher spatial resolution as compared to Landsat ETM. However in this case also, variation in the season of the image data collection and field data collection have influenced substantially. This could be clearly seen when we compare the relationships between the field measured crown cover and plot volume (Figure 3.14) to the relationship between the subpixel classified crown cover and plot volume (Figure 4.1).
3.15). Though, the correlation between the field measured CC and CC derived from Subpixel was quite high (Figure 3.11), the crown cover computed from the ASTER image didn't explain the variation of the plot volume as the crown cover measured from the field did (Figure 3.14).
5. Conclusions

The conclusions from this research are:

a. **Testing the Montes Method**
   Montes method to estimate the volume of a tree was not completely reliable because estimated volume of a same object changed with change in the tilt angle of the object, but there were possibilities for improvement.

b. **The model Stem Method**
   Tree volume estimated by proposed Model stem method was equivalent to the true volume irrespective of the tilt angle of the object. The proposed Model stem method, was therefore, independent of the tilt angles of the object and hence found to be more reliable than Montes method. In addition, the model stem method was more simple and easy to use.

c. **Suitability of the image classifiers for TROF detection**
   ERDAS Imagine subpixel classifier was better than FCD Mapper in detecting the TROF in Ghana. ASTER image was more suitable than Landsat ETM Image for the detection.

d. **Suitability of the image indices for Quantitative Assessment of the TROF**
   Both NDVI and Shadow Index were not suitable to assess the TROF volume per plot in the study area. A surrogate, crown cover derived from subpixel classification using ASTER image was a more suitable index for the quantitative assessment of the TROF in terms of volume per plot.

Finally, it can be concluded that a suitable amalgam of the field based and satellite based remote sensing and image classification techniques offer a huge potential for non-destructive assessment of the TROF.
6. Recommendations

More validation experiments should be conducted to make the photographic method operational. The proposed model stem approach from this research, was tested using only one tree. Though this method minimized the error due to branch tilt, it has not considered other errors that might occur due to photographic distortions. In a real world photographic distortions can be introduced due to the variation in distance between the object and the camera as well as the tilt angle of the camera itself. This may play a major role in the scale calculation and hence on the accuracy of the computed volume. This aspect should be considered in future research.

Satellite remote sensing together with new developments in image classification techniques offers unique capability in detection and quantitative assessment of the TROF. However to get maximum benefit of using these techniques and to extract most accurate information from these images, it is extremely necessary, in case of dynamic resource like TROF, that the time lag between the date of image acquisition and field verification should be kept as short as possible and preferably to match the same season.
7. Reference


8. Appendices

Appendix - 1: Trees outside forest as defined in Forest Resource Assessment definitions of FAO (adopted from Bellefontaine, et al., 2002)

FAO defines Trees outside forest as “Trees and shrubs of forest and non-forest species, on land not defined as forest and other wooded land” which includes: trees on land that fulfils the requirements of forest and other wooded land except that the area is less than 0.5 ha; trees able to reach a height of at least 5 m at maturity in situ but where the stocking level is below 5 percent; trees not able to reach a height of 5 m at maturity in situ but where the stocking level is below 10 percent; trees in shelterbelts and river galleries of less than 20m width and 0.5ha area; scattered trees in permanent meadows and pastures; permanent tree crops, orchards and fruit-tree meadows, industrial fruit trees, coconuts and date palms; trees in agroforestry systems such as coffee, cocoa, home garden; trees in urban environments and around infrastructures, such as parks and gardens, around buildings and in lines along streets, roads, railways, rivers, streams and canals.

Other land: land not classified as forest of other wooded land as defined above, includes agricultural land, meadows and pastures, built-on areas, barren land etc.

TROF Classification systems:
One of the TROF classification systems is given by (Kleinn, 2000) is according to the land where they are found
- Trees in urban and peri-urban areas
- Trees associated with permanent crops
- Trees associated with annual crops
- Trees associated with pastures
- Trees along line features such as property boarders, roads, railways, canals and creeks
- Tree groups (that do not comply with the area requirement of the forest definition)
- Trees on uncultivated/unmanaged lands (parts of savannah land, mountain regions and peat lands)

TROF can also be classified according to the purpose or the main use of tree into
Fuelwood trees; Fruit trees; Timber trees; Agro-forestry trees; Ornamental trees

It has generally been seen that TROF occurs in three main configurations. They could be individual trees (scattered throughout the landscape and not following any patterns), trees in lines and trees in groups.
Appendix - 2: Definition of forest in Forest Resource Assessment definitions of FAO

Land with tree crown cover (or equivalent stocking level) of more than 10 percent and area of more than 0.5 hectares (ha). The trees should be able to reach a minimum height of 5 meters (m) at maturity in situ. May consists either of closed forest formations where trees of various stores and undergrowth cover a high proportion of ground; or open forest formations with a continuous vegetation cover in which tree crown cover exceeds 10 percent. Young natural stands and all plantations established for forestry purposes which have yet to reach a crown density of 10 percent or tree height of 5 m are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention of natural causes but which are expected to revert to forest. Includes: forest nurseries and seed orchards that constitute an integral part of the forest; forest roads, cleared tracts, firebreaks and other small open areas; forest in national parks, nature reserves and other shelterbelts of trees with an area of more than 0.5 ha and width of more than 20m; plantations primarily used for forestry purposes, including rubber wood plantations and cork oak stands. Excludes: land predominantly used for agricultural practices

Other wooded land: land either with crown cover (or equivalent stocking level) of 5-10 percent of trees able to reach a height of 5m at maturity in situ; or a crown cover (or equivalent stocking level) of more than 10 percent of trees not able to reach a height of 5m at maturity in situ (e.g. dwarf or stunted trees); or with shrub or bush cover of more than 10 percent.

Tree: A woody perennial with a single main stem, or in the case of coppice with several stems, having a more or less definite crown. Includes: bamboos, palms and other woody plants meeting the above criterion.

Shrub and bushes: woody perennial plants, generally of more than 0.5 m and less than 5m and without a definite crown.
Appendix -3: Algorithms used in FCD Mapper

a. Vegetation Index (VI)
   i. NDVI ; Normalized Differential Vegetation Index (NOAA original)
   \[ NDVI = \frac{(NIR-R)}{(NIR+R)} \]

   ii. AVI ; Advanced Vegetation Index (ITTO/JOFCA Original)
   \[ AVI = (NIR \times (256-R) \times (NIR-R) + 1)^{1/3}, \ 0 < (NIR-R) \]

   iii. ANVI ; Advanced Normalized Vegetation Index
   ANVI; Synthesized Index from NDVI and AVI ,
   with Principal Component Analysis

b. Bare Soil Index (BI)
   \[ BI = \frac{((SWIR+R) - (B+NIR))}{((SWIR+R) + (B+NIR))} \]

c. Thermal Index (TI)
   TI; Calibrated Value of Thermal Band Information

d. Shadow Index (SI)
   \[ SI = [(256-B) \times (256-G) \times (256-R)]^{1/3} \]

After calculation of these indices vegetation density (VD) is calculated by combining vegetation index and bare soil index. These two indices with high negative correlation are combined using principal component analysis. The first principle component is scaled from zero to hundred percent points.

e. Advanced Shadow index (ASI): As the crown density increases, shadow index does not always increase relatively. To address this problem, advanced shadow index is calculated. For this maximum filter of 3x3 is run and the maximum value of the surrounding is taken. But care is taken to exclude the value where the VI is lower and TI is higher than standard. Those pixels are considered as gaps and black soil area and not as shadow from the trees.

f. Scaled shadow Index (SSI): Scaled shadow index is calculated from Advanced shadow index by linear transformation to integrate with vegetation density. For this the total available shadow value is stretched from 0% to 100%. The zero value of SSI corresponds with lowest shadow index and 100 % corresponds to highest possible shadow. From these indices the Forest canopy density is calculated as:

g. Forest Canopy Density (FCD) = (VD x SSI+1)^{1/2} - 1
Appendix - 4: Weighted linear regression as calculated by de Gier method

WEIGHTED LINEAR REGRESSION
===================================

DATE : 01-21-2005 (mm-dd-yyyy)
TIME : 14:17:56
PROGRAM FILE : polyreg.exe
DATA FILE : __regdat.prn
NAME OBJECT : Gh
# DATA SETS : 31

MODEL: \( Y = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 \)

\( Y \) = Volume
\( X_1 = d \) (dbh)
\( X_2 = d^2 \)
\( X_3 = d^3 \)

WEIGHT = \( \left( \frac{1}{X_1^{1.8}} \right)^2 \)

COEFFICIENTS

\( B_0 = -1.1736695175E-01 \)
\( B_1 = 2.1631280376E-02 \)
\( B_2 = -5.7562218325E-04 \)
\( B_3 = 1.7268208771E-05 \)

ANALYSIS OF VARIANCE

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VAR. RATIO (F) = 6.8395E+01

RES.MEAN SQUARE = 4.5208D-04

MEAN \( X_1 \) = 3.7677E+01
MEAN \( Y \) = 1.4322E+00

FURNIVAL INDEX = 2.4568E-01

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MULTIPLE CORRELATIONS

\( R^2 = 8.8376E-01 \)
\( R = 9.4011E-01 \)
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Non-significant variable \( X_2 \) will be removed

WEIGHTED LINEAR REGRESSION

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PROGRAM FILE : polyreg.exe
DATA FILE : __regdat.prn
NAME OBJECT : Gh
# DATA SETS : 31

MODEL: \( Y = B_0 + B_1 \cdot X_1 + B_2 \cdot X_2 \)

\( \text{Y} = V \)
\( X_1 = d \)
\( X_2 = d^3 \)

\( \text{WEIGHT} = (1/X_1^{1.8})^2 \)

COEFFICIENTS

\( B_0 = 2.8173370836E-02 \)
\( B_1 = 4.1889670390E-03 \)
\( B_2 = 1.2130330120E-05 \)

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RES.MEAN SQUARE= 4.4731E-04

\( \text{MEAN } X_1 = 3.7677E+01 \)
\( \text{MEAN } Y = 1.4322E+00 \)
FURNIVAL INDEX = 2.4308E-01

COVARIANCE MATRIX

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B_1 & -3.7024E-04 & 2.4395E-05 & -6.0068E-09 \\
B_2 & 8.3885E-08 & -6.0068E-09 & 2.3101E-12
\end{pmatrix}
\]

MULTIPLE CORRELATIONS

\[ R^2 = 8.8199E-01 \]
\[ R = 9.3917E-01 \]

CORRELATION MATRIX

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B_0 & B_1 & B_2 \\
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B_2 & 7.0534E-01 & -8.0016E-01 & 1.0000E+00
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SIGNIFICANCE COEFFICIENTS

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<td>4.9391E-03</td>
<td>8.4812E-01</td>
<td>-</td>
</tr>
<tr>
<td>B_2</td>
<td>1.5199E-06</td>
<td>7.9810E+00</td>
<td>&gt;0.1%</td>
</tr>
</tbody>
</table>

Non-significant variable \( X_1 \) will be removed

WEIGHTED LINEAR REGRESSION

DATE : 01-21-2005 (mm-dd-yyyy)
TIME : 14:17:56
PROGRAM FILE : polyreg.exe
DATA FILE : __regdat.prn
NAME OBJECT : Gh
# DATA SETS : 31

MODEL: \( Y = B_0 + B_1 \cdot X_1 \)

\[
Y = V \\
X_1 = d^3
\]

WEIGHT = \((1/X_1^{1.8})^2\)

COEFFICIENTS

\[
B_0 = 9.1748300540E-02 \\
B_1 = 1.3161790630E-05
\]
ANALYSIS OF VARIANCE

<table>
<thead>
<tr>
<th></th>
<th>SS</th>
<th>df</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>REG.</td>
<td>6.65580E-06</td>
<td>1</td>
<td>6.65580E-06</td>
</tr>
<tr>
<td>RES.</td>
<td>5.74626E-06</td>
<td>29</td>
<td>1.98147E-07</td>
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<tr>
<td>TOT.</td>
<td>1.24021E-05</td>
<td>30</td>
<td>4.13402E-07</td>
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VAR. RATIO (F) = 2.1049E+02

RES.MEAN SQUARE = 4.4514E-04

MEAN X = 3.7677E+01
MEAN Y = 1.4322E+00

FURNIVAL INDEX = 2.4190E-01

COVARIANCE MATRIX

<table>
<thead>
<tr>
<th></th>
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<th>B₁</th>
</tr>
</thead>
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<td>-7.2083E-09</td>
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<td>-7.2083E-09</td>
<td>8.2300E-13</td>
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</tbody>
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MULTIPLE CORRELATIONS

R² = 8.7896E-01
R = 9.3755E-01

CORRELATION MATRIX

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<th>B₁</th>
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<tbody>
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<tr>
<td>B₁</td>
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</tbody>
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SIGNIFICANCE COEFFICIENTS

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<th>Coeff.</th>
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<th>t</th>
<th>significance</th>
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<td>&gt;0.1%</td>
</tr>
<tr>
<td>B₁</td>
<td>9.0720E-07</td>
<td>1.4508E+01</td>
<td>&gt;0.1%</td>
</tr>
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</table>
Appendix - 5: Experiment 1: The cylinder and truncated cone used to test Montes method

The cylinder and cone that were used in experiment 1 for testing the existing Montes method when the objects tilt at different angles with respect to the grid lines.

A cylinder and a frustum of truncated cone (FoC) of dimensions as shown in Figure 8.2 was constructed. Since Montes method uses a photograph and not the true objects itself for the purpose of coding and volume computation, a view of those shapes (Figure 7.2 as they can be seen in a photograph (Figure 8.1) were also constructed. The views represent the photograph of the objects under consideration. These photographs were used as background images in the excel spreadsheet and coded separately using three different square grids of lengths 2 mm, 3 mm and 4 mm. The volume of each object was computed using the method proposed by Montes et al. (2000), as described in section 2.2. The photograph of the cylinder and the truncated cone were tilted at angles ranging from $0^\circ$ to $90^\circ$ at an interval of $10^\circ$ each with respect to the grid line used to code it. The error due to tilt was calculated and expressed as the percentage of the true volume as mentioned by the formula below.
\[ \text{Error Percent} = \frac{(\text{Calculated volume} - \text{True volume}) \times 100}{\text{True Volume}} \]

The true volume of a cylinder  
\[ = \frac{1}{4} \pi H \times D^2 \]
\[ = \frac{1}{4} \times \pi \times 8 \text{cm} \times (4 \text{cm})^2 \]
\[ = 100.53 \text{ cu cm} \]

The true volume of the cone  
\[ = \frac{\pi \times h}{3} \times \left( R^2 + r^2 + Rr \right) \]
\[ = \pi \times 6 \times (2^2 + 1^2 + 1 \times 2) \text{ cu cm} \]
\[ = 43.98 \text{ cu cm} \]

Percent error calculated for:

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<tr>
<th>Grid cell size</th>
<th>Tilt in degrees</th>
<th>2mm</th>
<th>3mm</th>
<th>4mm</th>
</tr>
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<tbody>
<tr>
<td>a. Truncated Cone</td>
<td>0</td>
<td>0.69</td>
<td>1.82</td>
<td>4.85</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.24</td>
<td>1.82</td>
<td>4.22</td>
</tr>
<tr>
<td></td>
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<td>4.30</td>
<td>7.05</td>
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<tr>
<td></td>
<td>40</td>
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<td>14.89</td>
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<td></td>
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<td>15.54</td>
<td>20.40</td>
<td>23.74</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>9.97</td>
<td>14.89</td>
<td>16.50</td>
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<tr>
<td></td>
<td>60</td>
<td>3.23</td>
<td>7.33</td>
<td>8.31</td>
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<tr>
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<td>70</td>
<td>1.45</td>
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<td>1.24</td>
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<tr>
<td></td>
<td>90</td>
<td>0.69</td>
<td>1.82</td>
<td>4.85</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>Grid cell size</th>
<th>Tilt in degrees</th>
<th>2mm</th>
<th>3mm</th>
<th>4mm</th>
</tr>
</thead>
<tbody>
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<td>2.44</td>
<td>0.00</td>
</tr>
<tr>
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<td>2.50</td>
<td>2.19</td>
</tr>
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<td></td>
<td>20</td>
<td>1.07</td>
<td>2.91</td>
<td>5.39</td>
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<td>30</td>
<td>4.53</td>
<td>5.99</td>
<td>8.60</td>
</tr>
<tr>
<td></td>
<td>40</td>
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<td>45</td>
<td>19.60</td>
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<td>4.53</td>
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<td>90</td>
<td>0.00</td>
<td>2.44</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Appendix - 6: Calculation of the scale of the photograph

Scale was calculated as the ratio of the true size of the object to the number of grid cells that represent that size. Since I used the digital camera to take the photograph, the problem of using the resolution of the scanner as explained in scale calculation by Montes method in section 2.2. (Montes, et al., 2000) becomes irrelevant and scale simply becomes the ratio of true size of the object to the number of grid cells that represented the size. For example take the same example of a cylinder in Appendix 5. Its height is 8cm. Suppose a grid of 2mm is used to code this object 40 grid cells will be accommodated along the length of the cylinder. Therefore the scale simply becomes ratio of the length of the cylinder to the number of grid cells. In this case 8/40 = 0.20.

The scale here simply means how much size (one dimension) in the reality does a grid cell correspond to.
Appendix - 7: Experiment 2: The hypothetical tree

The dimension of each of the three cones are same as that of Figure 7.2 in Appendix 5

The true volume of the hypothetical tree = 3 x volume of individual FoC
= 3 x 43.98 cubic centimetre (cu cm)
= 131.94 cu cm

Montes method codes the trunk and the branch differently and also measures the diameter based on the tilt angle of the branches. In Figure 7.3 the diameter of the two branches have to be measured along the column because the branches’ tilt angle is more than 45°.

Using the Montes method the total volume of this tree was calculated as

Total Volume = (61.057 + 76.998) for the trunk and the branches respectively
= 138.055 cu cm
The difference in computed volume using existing method = 6.11 cc so Percent Error = 4.63% (overestimation)

The model stem:

Figure 8.4: Model Stem

The model FoC had the same base, apex diameter and the total Face Surface Area as the hypothetical tree as shown in figure 8.3. The only unknown variable is its height which has to be calculated. Height was computed by adding all the grid cells which represented the total height of the model FoC. After multiplying the number of grid cells with the scale the height was known. Since, all the three
variables, base and apex diameter, and the height of the model FoC were known, the volume of this model FoC was calculated using the volume formula of FoC as explained in Appendix 5.

Scale of the photograph = 0.3333 cm per grid cell
Base Diameter = 12 grid cells
   = 12 x 0.3333 cm
   = 4 cm
Apex diameter = 6 grid cells
   = 6 x 0.3333 cm
   = 2 cm
Height of model FoC = 54 grid cells
Height = 54 x 0.3333
   = 18 cm

Using formula to compute the volume of the FoC,
The volume of model FoC = 131.95
True volume = 131.94
Difference in volume computed = 0.01 cu cm
Percent Error = 0.013 % (overestimation)
Appendix - 8: Experiment 3: Photo showing validation of model stem method using a real tree.

A. A real tree photograph

B. Model Stem of the tree
Appendix - 9: Signature evaluation report

Signature Evaluation Report

Source Image File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.img
Environment Correction File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.corenv
Detection Image File: d:/msc research work/image analysis sub pixel/working directory/tofinghana.img
Input Signature File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.img.185544.78.asd
Input False Alarm Aoi File: d:/msc research work/image analysis sub pixel/working directory/falsesignature.aoi
Input Valid Aoi File: d:/msc research work/image analysis sub pixel/working directory/truesignature.aoi
Classification Tolerance: 1

The number of signature evaluated: 1

The evaluation value is 0.284870

Signature Evaluation Report

Source Image File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.img
Environment Correction File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.corenv
Detection Image File: d:/msc research work/image analysis sub pixel/working directory/tofinghana.img
Input Signature File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.img.185544.84.asd
Input False Alarm Aoi File: d:/msc research work/image analysis sub pixel/working directory/falsesignature.aoi
Input Valid Aoi File: d:/msc research work/image analysis sub pixel/working directory/truesignature.aoi
Classification Tolerance: 1

The number of signature evaluated: 1

The evaluation value is 0.310605

Signature Evaluation Report

Source Image File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.img
Environment Correction File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.corenv
Detection Image File: d:/msc research work/image analysis sub pixel/working directory/tofinghana.img
Input Signature File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.img.185544.77.asd
Input False Alarm Aoi File: d:/msc research work/image analysis sub pixel/working directory/falsesignature.aoi
Input Valid Aoi File: d:/msc research work/image analysis sub pixel/working directory/truesignature.aoi
Classification Tolerance: 1

The number of signature evaluated: 1

The evaluation value is 0.369924

Signature Evaluation Report

Source Image File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.img
Environment Correction File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.corenv
Detection Image File: d:/msc research work/image analysis sub pixel/working directory/tofinghana.img
Input Signature File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.img.185544.15.asd
Input False Alarm Aoi File: d:/msc research work/image analysis sub pixel/working directory/falsesignature.aoi
Input Valid Aoi File: d:/msc research work/image analysis sub pixel/working directory/truesignature.aoi
Classification Tolerance: 1

The number of signature evaluated: 1

The evaluation value is 0.404970

Signature Evaluation Report

Source Image File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.img
Environment Correction File: d:/msc research work/image analysis sub pixel/working directory/correctedaster.corenv
Detection Image File: d:/msc research work/image analysis sub pixel/working directory/tofinghana.img
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Input False Alarm Aoi File: d:/msc research work/image analysis sub pixel/working directory/falsesignature.aoi
Input Valid Aoi File: d:/msc research work/image analysis sub pixel/working directory/truesignature.aoi
Classification Tolerance: 1

The number of signature evaluated: 1

The evaluation value is 0.408647
Appendix - 10: Outliers identification using SYSTAT version 7.0.1.

SYSTAT VERSION 7.0.1
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Welcome to SYSTAT!

>IMPORT 'C:\DOCUME~1\BISHWAS\MYDOCU~1\SYSTAT.XLS' / TYPE=EXCEL

IMPORT successfully completed.

>MGLH

>ESTIMATE /

Dep Var: PV_LSAT  N: 80  Multiple R: 0.43  Squared multiple R: 0.19

Adjusted squared multiple R: 0.17  Standard error of estimate: 16.41

Effect        Coefficient    Std Error    Std Coef Tolerance   t   P(2 Tail)
CONSTANT              3.91         2.86         0.0        .       1.37     0.18
FIELD_FCD              0.35         0.08         0.43      1.00     4.21     0.00

Analysis of Variance

Source             Sum-of-Squares   df   Mean-Square   F-ratio   P
Regression               4774.33     1  4774.33       17.72  0.00
Residual                21014.03    78   269.41

*** WARNING ***
Case    11 is an outlier  (Studentized Residual = 4.32)
Case    40 is an outlier  (Studentized Residual = 5.26)

Durbin-Watson D Statistic  1.796
First Order Autocorrelation  0.093

>EDIT

>DELETE 40

>DELETE 11

>MODEL PV_LSAT = CONSTANT + FIELD_FCD

>ESTIMATE /
Dep Var: PV_LSAT  N: 78  Multiple R: 0.58  Squared multiple R: 0.33

Adjusted squared multiple R: 0.32  Standard error of estimate: 12.15

Effect          Coefficient    Std Error     Std Coef Tolerance     t   P(2 Tail)
CONSTANT              1.41         2.14         0.0        .       0.66     0.51
FIELDFCD              0.38         0.06         0.58      1.00     6.13     0.00

Analysis of Variance

Source          Sum-of-Squares   df  Mean-Square     F-ratio       P
Regression               5544.93     1      5544.93       37.57        0.00
Residual                11215.45    76       147.57
-------------------------------------------------------------------------------

*** WARNING ***
Case            4 is an outlier        (Studentized Residual =         3.93)
Case           30 is an outlier        (Studentized Residual =         3.64)
Case           41 is an outlier        (Studentized Residual =         3.56)

Durbin-Watson D Statistic     1.951
First Order Autocorrelation  0.007

>DELETE 41
>DELETE 30
>DELETE 4
>MODEL PV_LSAT = CONSTANT + FIELDFCD
>ESTIMATE /

Dep Var: PV_LSAT  N: 75  Multiple R: 0.62  Squared multiple R: 0.39

Adjusted squared multiple R: 0.38  Standard error of estimate: 8.87

Effect          Coefficient    Std Error     Std Coef Tolerance     t   P(2 Tail)
CONSTANT              1.50         1.56         0.0        .       0.96     0.34
FIELDFCD              0.31         0.05         0.62      1.00     6.77     0.00
Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum-of-Squares</th>
<th>df</th>
<th>Mean-Square</th>
<th>F-ratio</th>
<th>P</th>
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</thead>
<tbody>
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<td>3606.26</td>
<td>45.81</td>
<td>0.00</td>
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<tr>
<td>Residual</td>
<td>5746.70</td>
<td>73</td>
<td>78.72</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*** WARNING ***
Case 30 is an outlier (Studentized Residual = 5.45)
Case 37 is an outlier (Studentized Residual = 3.41)

Durbin-Watson D Statistic 1.923
First Order Autocorrelation 0.021

>DELETE 37
>DELETE 30

>MODEL PV_LSAT = CONSTANT + FIELD_FCD

>ESTIMATE /

Dep Var: PV_LSAT  N: 73  Multiple R: 0.67  Squared multiple R: 0.45

Adjusted squared multiple R: 0.44  Standard error of estimate: 6.75

Effect   Coefficient   Std Error   Std Coef  Tolerance   t   P(2 Tail)
CONSTANT  1.62         1.19         0.0        1.35     0.18
FIELD_FCD 0.27         0.04         0.67       1.00     7.58     0.00

Analysis of Variance

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<th>F-ratio</th>
<th>P</th>
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<tr>
<td>Residual</td>
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<td>71</td>
<td>45.52</td>
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</table>

*** WARNING ***
Case 16 is an outlier (Studentized Residual = 4.08)

Durbin-Watson D Statistic 1.699
First Order Autocorrelation 0.131

>DELETE 16

>MODEL PV_LSAT = CONSTANT + FIELD_FCD
>ESTIMATE /

Dep Var: PV_LSAT  N: 72  Multiple R: 0.67  Squared multiple R: 0.44

Adjusted squared multiple R: 0.44  Standard error of estimate: 6.11

<table>
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<tr>
<th>Effect</th>
<th>Coefficient</th>
<th>Std Error</th>
<th>Std Coef</th>
<th>Tolerance</th>
<th>t</th>
<th>P(2 Tail)</th>
</tr>
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<tbody>
<tr>
<td>CONSTANT</td>
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<td>0.0</td>
<td>1.74</td>
<td>0.09</td>
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<td>FIELDPCD</td>
<td>0.24</td>
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<td>0.67</td>
<td>1.00</td>
<td>7.49</td>
<td>0.00</td>
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Analysis of Variance

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<th>Mean-Square</th>
<th>F-ratio</th>
<th>P</th>
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<td>37.29</td>
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</tbody>
</table>

Durbin-Watson D Statistic  1.421
First Order Autocorrelation  0.271
Appendix - 11: Significance test of the different order polynomials that relate Plot volume with Crown Cover

A. Plot volume with Crown cover measured in the field

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Welcome to SYSTAT!

>IMPORT 'C:\DOCUME~1\BISHWAS\MYDOCU~1\SYSTAT1.XLS' / TYPE=EXCEL
IMPORT successfully completed.

>EDIT

>PLOT PV_LSAT*FIELDFCD / XLABEL='Field crown cover' XMIN=0 XMAX=100 ,
>YLABEL='Plot volume (Landsat)' YMIN=0 YMAX=90

>MODEL PV_LSAT = CONSTANT + FIELDFCD

>ESTIMATE

Dep Var: PV_LSAT  N: 69  Multiple R: 0.71  Squared multiple R: 0.51

Adjusted squared multiple R: 0.50  Standard error of estimate: 5.78

Effect  Coefficient  Std Error  Std Coef  Tolerance  t  P(2 Tail)
CONSTANT  1.07  1.05  0.0  1.02  0.31
FIELDFCD  0.26  0.03  0.71  1.00  8.27  0.00

Analysis of Variance

Source  Sum-of-Squares  df  Mean-Square  F-ratio  P
Regression  2290.01  1  2290.01  68.46  0.00
Residual  2241.09  67  33.45

Durbin-Watson D Statistic  1.242
First Order Autocorrelation  0.355

>MODEL PV_LSAT = CONSTANT + FIELDFCD+FIELDFCD*FIELDFCD

>ESTIMATE

Dep Var: PV_LSAT  N: 69  Multiple R: 0.72  Squared multiple R: 0.51
Adjusted squared multiple R: 0.50  Standard error of estimate: 5.79

Effect         Coefficient    Std Error     Std Coef Tolerance     t   P(2 Tail)
CONSTANT              0.29         1.35         0.0        .       0.21         0.83
FIELDCD              0.34         0.10         0.94      0.11     3.60       0.00
FIELDCD
*FIELDCD            -0.00         0.00        -0.25      0.11    -0.94     0.35

Analysis of Variance

Source             Sum-of-Squares   df  Mean-Square     F-ratio       P
Regression               2319.68     2      1159.84       34.62        0.00
Residual                 2211.41    66        33.51
-------------------------------------------------------------------------------

*** WARNING ***
Case            1 has large leverage   (Leverage =         0.32)
Case           25 has large leverage   (Leverage =         0.24)

Durbin-Watson D Statistic     1.353
First Order Autocorrelation  0.309

>MODEL PV_LSAT = CONSTANT + FIELDCD+FIELDCD*FIELDCD+FIELDCD*FIELDCD*FIELDCD*,
>FIELDCD

>ESTIMATE

Dep Var: PV_LSAT   N: 69   Multiple R: 0.73   Squared multiple R: 0.53

Adjusted squared multiple R: 0.51  Standard error of estimate: 5.74

Effect         Coefficient    Std Error     Std Coef Tolerance     t   P(2 Tail)
CONSTANT              1.58         1.59         0.0        .       0.99         0.33
FIELDCD              0.06         0.21         0.18      0.02     0.31       0.76
FIELDCD
*FIELDCD             0.01         0.01         1.75      0.00    1.28      0.20
FIELDCD
*FIELDCD
FIELDCD
*FIELDCD            -0.00         0.00        -1.31      0.01    -1.49     0.14

Analysis of Variance

Source             Sum-of-Squares   df  Mean-Square     F-ratio       P
Regression               2392.72     3      797.57       24.24        0.00
A NON-DESTRUCTIVE APPROACH FOR QUANTITATIVE ASSESSMENT OF TREE RESOURCES OUTSIDE THE FOREST

Residual 2138.37 65 32.90

*** WARNING ***
Case 1 has large leverage (Leverage = 0.50)
Case 25 has large leverage (Leverage = 0.29)

Durbin-Watson D Statistic 1.395
First Order Autocorrelation 0.293

B. Plot volume with crown cover derived from Sub pixel classification

>MODEL PV_ASTER = CONSTANT + SP_CC

>ESTIMATE

Dep Var: PV_ASTER  N: 69  Multiple R: 0.55  Squared multiple R: 0.30

Adjusted squared multiple R: 0.29  Standard error of estimate: 1.72

Effect  Coefficient  Std Error  Std Coef Tolerance  t  P(2 Tail)
CONSTANT 0.36 0.35 0.0 1.01 0.32
SP_CC  0.05 0.01 0.55 1.00 5.40 0.00

Analysis of Variance

Source Sum-of-Squares df Mean-Square  F-ratio  P
Regression 85.80 1 85.80 29.12 0.00
Residual 197.39 67 2.95

Durbin-Watson D Statistic 1.300
First Order Autocorrelation 0.344

>MODEL PV_ASTER = CONSTANT + SP_CC+SP_CC*SP_CC

>ESTIMATE

Dep Var: PV_ASTER  N: 69  Multiple R: 0.55  Squared multiple R: 0.31

Adjusted squared multiple R: 0.29  Standard error of estimate: 1.72

Effect  Coefficient  Std Error  Std Coef Tolerance  t  P(2 Tail)
CONSTANT 0.47 0.40 0.0 1.18 0.24
A NON-DESTRUCTIVE APPROACH FOR QUANTITATIVE ASSESSMENT OF TREE RESOURCES OUTSIDE THE FOREST

<table>
<thead>
<tr>
<th>SP_CC</th>
<th>0.04</th>
<th>0.03</th>
<th>0.39</th>
<th>0.14</th>
<th>1.41</th>
<th>0.16</th>
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<tbody>
<tr>
<td>SP_CC*SP_CC</td>
<td>0.00</td>
<td>0.00</td>
<td>0.17</td>
<td>0.14</td>
<td>0.63</td>
<td>0.53</td>
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Analysis of Variance

<table>
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<th>Source</th>
<th>Sum-of-Squares</th>
<th>df</th>
<th>Mean-Square</th>
<th>F-ratio</th>
<th>P</th>
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<td>2</td>
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<td>Residual</td>
<td>196.21</td>
<td>66</td>
<td>2.97</td>
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*** WARNING ***
Case 1 has large leverage (Leverage = 0.47)

Durbin-Watson D Statistic 1.249
First Order Autocorrelation 0.363

>MODEL PV_ASTER = CONSTANT + SP_CC + SP_CC*SP_CC + SP_CC*SP_CC*SP_CC

>ESTIMATE

Dep Var: PV_ASTER  N: 69  Multiple R: 0.57  Squared multiple R: 0.32

Adjusted squared multiple R: 0.29  Standard error of estimate: 1.72

<table>
<thead>
<tr>
<th>Effect</th>
<th>Coefficient</th>
<th>Std Error</th>
<th>Std Coef</th>
<th>Tolerance</th>
<th>t</th>
<th>P(2 Tail)</th>
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</thead>
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<tr>
<td>CONSTANT</td>
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<td>0.0</td>
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<td>0.17</td>
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<td>SP_CC</td>
<td>-0.02</td>
<td>0.06</td>
<td>-0.23</td>
<td>0.03</td>
<td>-0.38</td>
<td>0.71</td>
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<tr>
<td>SP_CC*SP_CC</td>
<td>0.00</td>
<td>0.00</td>
<td>1.72</td>
<td>0.01</td>
<td>1.25</td>
<td>0.21</td>
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<tr>
<td>SP_CC<em>SP_CC</em>SP_CC</td>
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<td>0.00</td>
<td>-1.01</td>
<td>0.01</td>
<td>-1.15</td>
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Analysis of Variance

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<th>Source</th>
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<th>df</th>
<th>Mean-Square</th>
<th>F-ratio</th>
<th>P</th>
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<td>30.30</td>
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<tr>
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<td>2.96</td>
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*** WARNING ***
Case 1 has large leverage (Leverage = 0.87)

Durbin-Watson D Statistic 1.293
First Order Autocorrelation 0.346
Appendix - 12: Residual plots before and after applying weights

**Figure 8.5:** The residual plot showing the non constant residuals

**Figure 8.6:** The residual plot showing the constant residuals after weighing
Appendix - 13: Map datum of Ghana

<table>
<thead>
<tr>
<th>Grid</th>
<th>Ghana National</th>
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</thead>
<tbody>
<tr>
<td>Projection</td>
<td>Transverse Mercator</td>
</tr>
<tr>
<td>Datum</td>
<td>Leigon</td>
</tr>
<tr>
<td>Ellipsoid</td>
<td>Clarke 1880</td>
</tr>
<tr>
<td></td>
<td>$a = 6378249.145, \frac{1}{f} = 293.465$</td>
</tr>
<tr>
<td>Unit of Measurement</td>
<td>Meters</td>
</tr>
<tr>
<td>False Easting</td>
<td>274320.000</td>
</tr>
<tr>
<td>False Northing</td>
<td>0.0000</td>
</tr>
<tr>
<td>Central Meridian</td>
<td>1°00'0.00&quot; W</td>
</tr>
<tr>
<td>Central Parallel</td>
<td>0°00&quot;0.00&quot; N</td>
</tr>
<tr>
<td>Scale Factor at Origin</td>
<td>0.99975000</td>
</tr>
</tbody>
</table>
Appendix - 14: Ratio of dead to live tree in the study area.

Table 5: Ratio of dead tree to live tree in the study area

<table>
<thead>
<tr>
<th>Description</th>
<th>Number of trees</th>
</tr>
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<tbody>
<tr>
<td>Live trees</td>
<td>455</td>
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<tr>
<td>Dead trees</td>
<td>137</td>
</tr>
<tr>
<td>Ratio of dead to live trees</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 6: The frequency of occurrence of dead trees in the plots that were visited during the field work

<table>
<thead>
<tr>
<th>Description</th>
<th>Number of plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deliberate killing</td>
<td>22</td>
</tr>
<tr>
<td>Natural death</td>
<td>11</td>
</tr>
<tr>
<td>Plots with dead trees</td>
<td>33</td>
</tr>
<tr>
<td>Total plots</td>
<td>80</td>
</tr>
<tr>
<td>Percent of plots where dead trees were encountered</td>
<td>41.25</td>
</tr>
</tbody>
</table>

Figure 8.7: Burning to kill the tree

Figure 8.8: Ring barking to kill the tree

Figure 8.9: A hollow tree

Figure 8.10: Tree with Buttress
Appendix - 15: Sheet used to collect the data in the field

<table>
<thead>
<tr>
<th>Sample Point Number</th>
<th>Landcover type</th>
<th>Coordinates</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toposheet number</td>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Plot</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TROF Configuration</th>
<th>L</th>
<th>G</th>
<th>ST</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Tree Number</th>
<th>Number in photograph</th>
<th>Number in Subsampling</th>
<th>Species</th>
<th>DBH</th>
<th>Height</th>
<th>Crown Cover (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>
Appendix - 16: Demonstration of how the tree photos were joined together using Adobe Photoshop

Figure 8.11 (A) : Photo of the base of the tree
Figure 8.11 (B): Photo of the top of the tree
Figure 8.11 (C): The full tree photo after mosaic
### Appendix 17a: List of TROF species found in Ghana

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Local Name</th>
<th>Scientific Name</th>
<th>Family</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Afena</td>
<td>Strombosia glaucescens</td>
<td>Olacaceae</td>
</tr>
<tr>
<td>2</td>
<td>Akasaa</td>
<td>Chrysophyllum albidum</td>
<td>Sapotaceae</td>
</tr>
<tr>
<td>3</td>
<td>Akuokuonisu</td>
<td>Spathodia campanulata</td>
<td>Bignoniaceae</td>
</tr>
<tr>
<td>4</td>
<td>Akyee</td>
<td>Blighia sapida</td>
<td>Sapindaceae</td>
</tr>
<tr>
<td>5</td>
<td>Amangyedua</td>
<td>Ficus sagittifolia</td>
<td>Moraceae</td>
</tr>
<tr>
<td>6</td>
<td>Ankaa (Orange)</td>
<td>Citrus spp</td>
<td>Rosaceae</td>
</tr>
<tr>
<td>7</td>
<td>Asia/Essia</td>
<td>Pterisrhianthus macrocarp</td>
<td>Lecythidaceae</td>
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<tr>
<td>8</td>
<td>Atabene</td>
<td>Chrysophyllum papulchrum</td>
<td>Sapotaceae</td>
</tr>
<tr>
<td>9</td>
<td>Awiemfoo samena</td>
<td>Albizia ferruginea</td>
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<tr>
<td>10</td>
<td>Bese</td>
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<td>Sterculiaceae</td>
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<tr>
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<td>12</td>
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## Appendix 17b: Tree species found in forest reserve

<table>
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<th>Local Name</th>
<th>Scientific Name</th>
<th>Family</th>
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<tbody>
<tr>
<td>1</td>
<td>Abakammo</td>
<td>Tiegemella heckilii</td>
<td>Sapotaceae</td>
</tr>
<tr>
<td>2</td>
<td>Abako/Baku</td>
<td>Tieghemella heckilii</td>
<td>Sapotaceae</td>
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<tr>
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<td>Adweaa</td>
<td>Stigmaria longifolia</td>
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<td>Afena</td>
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<td>Akasaa</td>
<td>Chrysophyllum albidum</td>
<td>Sapotaceae</td>
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<tr>
<td>6</td>
<td>Akumabaa</td>
<td>Nesogordonia spp</td>
<td>Sterculiaceae</td>
</tr>
<tr>
<td>7</td>
<td>Akyee</td>
<td>Blighia sapida</td>
<td>Sapindaceae</td>
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<tr>
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<td>Aprokuma</td>
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<td>Apuro</td>
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<td>Asanfena</td>
<td>Aningeria altissima</td>
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<td>Albizia ferruginea</td>
<td>Mimosaceae</td>
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<td>Moraceae</td>
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<td>13</td>
<td>Dahoma</td>
<td>Piptadeniastrum africunum</td>
<td>Mimosaceae</td>
</tr>
<tr>
<td>14</td>
<td>Danta</td>
<td>Nesogordonia papaverifera</td>
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Appendix - 18: Symmetric orientation of object with respect to grid lines

Figure 8.12 (A): The object tilted at 30°

Figure 8.12 (B): The object tilted at 60° (B)

Figure 8.12 (C): The object properly aligned to the grid lines (C)

With increase in the tilt angle of the object beyond 45°, direction of the measurement of the diameter is switched from along the row to along the column. In the Figure 8.12 (C), the object in aligned properly with the grid lines and the tilt angle is 0°. The diameter is thus measured along the row shown between the two dark lines. In case of 8.12 (A), since the tilt angle is 30° only, the diameter is measured along the row marked by the thick red lines. If we look at the Figure 8.12 (B) the tilt angle of the object is more than 45° therefore, the direction of the measurement of the diameter is along the row. Also notice that the number of grid cells that constitute the diameter, marked by thick lines in Figure 8.11 (A and B) are equal. Since 30° tilt from the vertical axis means 60° tilt from the
horizontal. Now if we consider the reference as 45°, 30° tilt of the object in clockwise direction with respect to the vertical grid line means 15° tilt in anticlockwise direction from the 45° reference angle. Similarly, 60° tilt in anticlockwise direction from the horizontal grid line means 15 degree tilt in clockwise direction from the 45° reference angle. It means that the orientation of the object becomes symmetric with respect to 45° tilt angle. In this situation, if we also switch our diameter measuring direction to vertical when the tilt angle is more than 45°, due to this symmetry, the error also follows the decreasing trend once the tilt angle starts increasing beyond 45°.
Appendix – 19: Error in volume as a result of error in diameter measurement for a cylindrical object.

Let’s assume that the diameter across the row of the grid cells when it is perfectly aligning with the grid lines is D and the unit height of the grid cells be H

Then True volume of that row \( (V) = \frac{1}{4}\pi HD^2 \)

Let’s assume that due to the tilting effect of the tree an error of “e” is introduced in diameter measurement.

The diameter now will be \( (D+e) \) and the volume of the row \( (V_1) = \frac{1}{4}\pi \times (D+e)^2 \times H \)

\[
V_1 = \frac{1}{4}\pi H (D^2 + 2De + e^2)
\]

\[
V_1 = V + \frac{1}{2} \pi H (De + \frac{1}{2} e^2)
\]

Therefore, error in volume = \( \frac{1}{2} \pi H (De + \frac{1}{2} e^2) \)

= \( K(De + \frac{1}{2} e^2) \)