Evaluation of carbon accounting models for plantation forestry in South Africa

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Declaration

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Abstract

The role that forestry plays in climate change mitigation is well recognized by countries that ratified the Kyoto protocol agreement. Though climate change mitigation strategies provide a strong incentive to quantify current patterns of forest carbon sources and sinks, this exercise (carbon accounting) is not as simple as it sounds. This is proven by the vast number of techniques and methodologies available, from models to softwares programmes created in response to the need to estimate carbon sequestration.

The study aimed at gaining an understanding of the current carbon sequestration estimation methodology and models in use by the South African Forestry Industry. A survey was undertaken amongst forestry industry stakeholders in which 77% of respondents agreed to the need for a carbon sequestration model for South Africa. This model should have qualities that the forestry industry and all stakeholders agreed with. .

A search of freely available models and software was conducted. The aim was to find freely available model(s) that would be readily applicable and adoptable to South African conditions.

A Multi Criteria Analysis was carried out using "ideal qualities" for a carbon model as weighting. This resulted in the selection of two models, CASMOFOR and CBM CFS 3, which obtained the highest sum product total from the analysis. These together with FICAT, which came as a recommendation from the questionnaire survey, were compared in the analysis.

Carbon values were calculated from yield table volumes by Kotze *et al.* (2012). A conversion of these volumes to biomass and carbon was done using Dovey (2009) biomass expansion factors and a biomass to carbon conversion value of 0.5 g C/g dry matter, following procedures by Matthews (1993).

The first comparison was made on how the model results related to the yield table estimates from Kotze *et al*. (2012). When carbon values were compared per hectare, it was found that the FICAT model differed significantly from the rest.

A second comparison looked at the models' prediction of the carbon accumulated in NCT's Enon plantation outside Pietermaritzburg. The Hungarian model, CASMOFOR, was the better predictor as it produced the lowest Mean Squared Error (MSE).

Based on the results from the survey and model analysis a number of recommendations can be made regarding the current carbon accounting situation in South Africa. One of the main recommendations is that information sharing among the industry's stakeholders should improve if the industry is to reach consensus on which methodology to adopt in their business practices.

Opsomming

Die rol wat bosbou speel in klimaatsverandering-bekamping is welbekend onder lande wat die Kyoto protokol ooreenkoms onderteken het. Alhoewel klimaatsverandering-bekamping strategieë ‘n sterk aansporing bied om huidige patrone van woudkoolstof bronne en sinkte te kwantifiseer, is hierdie oefening nie so maklik soos dit klink nie. Die bewys hiervan is die groot aantal tegnieke en metodes, wat wissel van modelle tot sagteware programme wat ontwikkel is om koolstofsekwistrasie te meet.

Die doelwit van die studie was om die huidige koolstofsekwistrasie metodes en modelle wat deur die Suid Afrikaanse Bosbou Bedryf gebruik word, beter te verstaan. ‘n Vraelysopname is onderneem onder bosbou-industrie deelnemers, waarin 77% van respondente saamgestem het dat dit nodig is dat Suid Afrika ‘n koolstofsekwistrasie model moet hê. Die model moet eienskappe hê waarmee die bosbou-industrie en alle deelnemers saamstem.

‘n Soektog na vrylik beskikbare koolstofmodelle en sagteware programme is onderneem. Die doelwit was om modelle te vind wat geredelik aangepas kan word vir Suid Afrikaanse toestande. ‘n Multi-kriteria analise is uitgevoer met die “ideale eienskappe”vir ‘n koolstofmodel as gewigte. Die resultaat was die seleksie van twee modelle, CASMOFOR en CBM CFS 3, wat die hoogste telling in die ontleding behaal het. Hierdie modelle, tesame met FICAT, wat aanbeveel is deur respondente van die vraelys opname, is vergelyk in ‘n ontleding.

Koolstofwaardes is bereken vanaf opbrengstabelle wat deur Kotze *et al*. (2012) ontwikkel is. Die omsetting van hierdie volumes na biomassa en koolstof is gedoen deur Dovey (2009) se biomassa uitbreidingsfaktore en ‘n biomassa na koolstof omsettings faktor van 0.5 g C/g droëmassa te gebruik (Matthews, 1993). In die eerste vergelyking van die modelle is gekyk hoe die modelle vergelyk met koolstof berekeninge vanaf die Kotze *et al*. (2012) opbrengstabelle. Wanneer koolstofwaardes per hektaar vergelyk word is gevind dat FICAT beduidend verskil van die ander modelle. In ‘n tweede vergelyking is gekyk na hoe die modelle die koolstof wat in NCT se Enon plantasie buite Pietermaritzburg versamel is, voorspel. Die Hongaarse CASMOFOR model was die beste voorspeller. Anders as die FICAT en CBM CFS 3 modelle het dit die laagste Gemiddelde Vierkante Fout gehad.

Na gelang van die resultate van die vraelysopname en die modelontleding kan ‘n aantal aanbevelings gemaak word oor die huidige koolstofberekening situasie in Suid Afrika. Een

van die hoof aanbevelings is dat die uitruil van inligting tussen industrie deelnemers moet verbeter as die bedryf eenstemmigheid oor die metode van koolstofberekening wil bereik.

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Acronyms

ACCA	Association of Chartered Certified Accountants
AGO	Australian Greenhouse Office
BEF	Biomass Expansion Factors
CASMOFOR	Carbon Sequestration model for forestations
CBM CFS 3	Carbon Based Model for Canadian Forestry Service
CDP	Carbon Disclosure Project
CEPI	Confederation of European Paper Industries
CIFOR	Center for International Forestry Research
CO_2	Carbon Dioxide
CSR	Corporate and Social Responsibility
DAFF	Department of Agriculture Fisheries and Forestry
DBH	Diameter at Breast Height
DM	Dry Matter
FAO	Food and Agriculture Organisation
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FICAT	Forestry Industry Carbon Assessment Tool
FSA	Forestry South Africa
FSC	Forestry Stewardship Council
GHG	Greenhouse Gases
GPP	Green Peace Policy
GPS	Geographical Positioning System

Gt	Giga tons
ICFR	Institute for Commercial Forestry Research
1PCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index
LCA	Life Cycle Assessment
IPCC	Intergovernmental Panel on Climate Change
MAI	Mean Annual Increment
MCA	Multi Criteria Analysis
MSH	Management Science for Health
NCASI	National Council for Air and Stream Improvement
NGO	Non-Governmental Organisation
PAMSA	Paper Manufacturers Association of South Africa
QGIS	Quantum Geographic Information System
REDD+ (REDD)	Reducing Emissions from Deforestation and Forest Degradation
RSA	Republic of South Africa
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations Children's Fund

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Chapter 1

1.1 General introduction

South African plantation forestry is based on exotic trees and cover 1.04% of cultivated land. In 2010/2011 the total turnover for the Forestry Industry was in the region of R21.4 billion and the industry employed in excess of 200 000 people. The main products produced by the Forestry Industry are pulp (60.1%), sawn lumber (18.9%), wood chips (7.5%), panels (7.0%) and mining timber (1.7%) (FSA, 2013). The private sector currently owns 70% of the total plantation area, as well as virtually all the processing plants (DAFF, 2012).

South Africa's plantations are not only important from a commercial point of view. They are also recognized as sources of environmental services such as carbon sequestration (Mander, 2012). Forest carbon sequestration is increasingly recognized as an ecosystem service that are included as indices of sustainability as well as in modeling exercises that seek to examine interactions among multiple ecosystem services (McDonald & Lane, 2004; Nelson *et al.,* 2009 cited by Turner *et al*., 2011).

The role that forest management can play in a climate change mitigation strategy provides a strong incentive to quantify current patterns of forest carbon sources and sinks, especially as they relate to forest management. This is one of the key issues in the Kyoto protocol agreement (Corbera & Schroeder, 2011). There is widespread interest in managing forests to increase the rate of carbon dioxide (CO_2) sequestration (Pacala & Socolow, 2004) because sequestering and storing carbon in forests is relatively inexpensive when compared to efforts aimed at actually reducing emissions in fossil fuel intensive economies (Angelsen & Atmadja, 2008).

Carbon stock estimation is important for scientific and management issues such as forest productivity, nutrient cycling, and inventories of fuel wood and pulp. In addition, aboveground biomass is a key variable in the annual and long term changes in the global terrestrial carbon cycle and other earth system interactions. Not only that, it's important in the modeling of carbon uptake and redistribution within ecosystems. Of interest to scientists is live wood biomass, which is involved in the regulation of atmospheric carbon concentrations (Terakunpisut *et al.* 2007).

Carbon sequestration can also be linked to the corporate bottom line, either directly as a source of income from carbon trading or indirectly as part of carbon footprint reporting (Primer, 2008) and for this reason carbon sequestration potential will need to be estimated for forests sooner rather than later. Its quantity should be tied to the precision and accuracy of carbon sequestration estimates (Johnsen *et al.*, 2004; Birdsey *et al.,* 2006).

1.2 Study rationale

Given their ability to absorb and store CO_2, forests can help counteract or moderate climate change. Trees serve as "sinks" within the carbon cycle by absorbing and sequestering CO_2 from the atmosphere. Growing sustainably managed forests thus contributes to reducing CO_2 levels in the atmosphere. It is estimated that carbon sequestration of South African plantations results in the avoidance of about 4.1 million tonnes of CO_2 per year (Mondi, 2012).

While there are a number of carbon calculation models and computer programmes available globally to estimate the amount of carbon sequestered by trees (Matthews, 2005), current literature show that only one, the Australian 3PG model, has been tested in South Africa (Landsberg & Waring, 1997; ICFR, 2008). It is therefore important that the South African Forestry Industry should test the accuracy of other models for the various commercial species before adopting any.

Realistic estimates of carbon stocks are crucial because they indicate the potentiality of vegetation to release or absorb carbon. Secondly, a time series of the carbon stock in vegetation can be used in the calculations of carbon net flux by means of inverse modelling. (Goodale *et al.,* 2002 cited by Alamgir & Al-Amin, 2008), and hence further research should endeavor to improve the accuracy of estimates across a broad array of forest conditions (Maier and Johnsen, 2010).

This study aims at identifying and testing carbon sequestration models that could potentially be used by the South African Forestry Industry. The study will also recommend whether or not South Africa should design its own model, specific to South African conditions and species.

1.3 Study objectives

Carbon is stored in forests not only in the above and belowground biomass of trees, but also in other aboveground vegetation, in litter and in soils, but because of inadequate information related to carbon storage in these components it was not included in this study. The scope of this study was limited to above ground carbon sequestration.

The aim of this study is to identify and test the ability of selected available carbon model(s) to predict carbon sequestered in commercial plantation species in South Africa.

The study has the following objectives:

- Gain an understanding of the current carbon sequestration methods employed in the South African Forestry Industry.
- Select from a range of available carbon models/ programmes the most suitable models for South African conditions.
- Compare the model(s) selected on data from the NCT Enon plantation.

The objectives will be met by answering the following research questions:

- What is the view of the forestry industry on what a good carbon model by South African standards should be?
- Which model(s) have already been tested in South Africa?
- Which carbon models are currently in use elsewhere?
    - In which regions have they been developed?
    - What input requirements (variables) do they need to function?
    - Are the models/tools freely available (open source)?
    - Are there any other special training or data requirements for their operation?
- What is the amount of carbon calculated by biomass expansion functions developed by Dovey (2009) for South African conditions?
- How does the output from selected models compare to the output of biomass expansion functions developed by Dovey (2009)?

The following research activities took place:

- Literature search to identify potential carbon models and computer programmes.
- First level selection of available models and programmes.
- Key informant questionnaire survey in the South African Forestry Industry to determine carbon model requirements and to gather information about the carbon estimation *status quo* in SA.
- Development of a multi criteria decision framework (based on survey responses) to evaluate the selected models and programmes.
- Enumeration of the NCT Enon plantation and estimation of the carbon stock from this plantation based on Dovey (2009) biomass expansion functions.
- Parameterization of the two most preferred carbon models and comparison with the Dovey (2009) biomass expansion functions.

1.4 Thesis structure

This thesis consists of seven chapters:

- Chapter 2: Focuses on the literature study surrounding carbon modelling, looking from a global perspective on how South Africa fits into the broader carbon sequestration picture.
- Chapter 3: Outlines the step by step methodology followed in the study as well as the data analysis techniques used.
- Chapter 4: Presents the results obtained from the data collection and data analysis.
- Chapter 5: Discusses the results and touches on other issues of interest in relation to the results.
- Chapter 6: Gives an overview of the findings of the study as well as some recommendations.

Chapter 2: Literature Review

2.1Introduction

The role of forestry in climate change mitigation is well recognized (FAO, 2012), but forest carbon accounting is not as simple as it seems. Forests are variable, with a broad array of plant species (both trees and understory vegetation). The myriad permutations of forest plants and soils present obstacles for estimating existing carbon stocks and carbon flows that result from forestry activities (Gorte, 2009). The scientific community has responded to this challenge by creating carbon models and computer programmes that can be used to estimate carbon sequestration of various forest types. In the process of evaluating and selecting appropriate carbon models for the South African Forestry Industry it is necessary to understand how forest carbon sequestration works and how it links to the current climate change debate.

2.2 Forestry industry and the global carbon cycle

In the forestry industry the connections between climate change concerns and the product value chain are perhaps more complex than in any other industry. The forests that supply the industry's raw material remove CO_2 from the atmosphere and store carbon not only in the wood, but also below ground in soil and root systems as well as ultimately in forest products. Forests and their carbon sequestration potential are affected by management practices, climate and the rise in atmospheric CO_2 (FAO, 2010).

Reaching an agreement on ways to account for carbon sequestration in forests has been difficult. This is due to differences in the types and extents of forests between countries. The generally proposed models for estimating changes in carbon storage are: "Land-based carbon models" which describe the carbon that is stored and emitted from different production systems and ecosystems; and "activity-based models" which describe individual activities such as the processing of timber into pulp and paper. The ambiguous language and terminology used by land based carbon models contribute to the inherent difficulties of measuring baseline carbon stocks, land uses, the carbon impacts of various activities and "leakage" (shifting land or product uses). At the same time diverse forest types and widespread disputes over the carbon consequences of various practices make it difficult to generalize about the opportunities to mitigate global climate change through forest carbon sequestration (FAO, 2010).

2.1.1. Forest carbon sequestration

Despite the difficulty in estimating the amount of carbon stored in forests it is an accepted fact that the worlds' forests store and cycle enormous quantities of carbon. It is estimated that the world's forests can store 283 gigatonnes (Gt) of carbon in their biomass alone, and that this plus the carbon stored in dead wood, litter and soil is more than the 762 Gt of carbon in the atmosphere (FAO, 2007; IPCC, 2007a). The total annual turnover of carbon between the forests and the atmosphere (as characterized by gross primary production) is in the range of 55 to 85 Gt^{-1} (Field *et al.,* 1998, IPCC, 2000; Sabine *et al.*, 2004). The amount of atmospheric carbon transformed into forest biomass, which is essentially equal to net primary production, has been estimated at 25 to 30 Gt^{-1} (Field, 1998; Sabine *et al.*, 2004). In comparison, the amounts of carbon removed from global forests in industrial round wood are small, at approximately 0.42 Gt^{-1} (FAO, 2007).

Even though the deforestation rate and loss of forest from natural causes is still alarmingly high (FAO, 2010), however at the global level, it decreased from an estimated 16 million ha^{-1} in the 1990s to around 13 million ha^{-1} in the last decade. At the same time, afforestation and natural expansion of forests in some countries and areas reduced the net loss of forest area significantly at the global level. The net loss in forest area in the period 2000–2010 was estimated at 5.2 million ha^{-1} (an area about the size of Costa Rica), down from 8.3 million ha^{-1} in the period 1990–2000 (FAO, 2011).

Loss of forested area is associated with transfers of carbon to the atmosphere. In the 1990s, carbon loss was estimated to average 1.6 Gt^{-1}, ranging from 0.5 to 2.7 Gt, which represented about 20% of global carbon emissions in this period (IPCC, 2007a). It is difficult to determine how the amounts of carbon are changing at the global level for areas that remain in forest, and efforts to develop global carbon budgets have found a large unexplained uptake of carbon by the terrestrial ecosystem. Since this residual land sink is not well understood, some explanations have been proposed, including continuing accumulation of carbon in undisturbed tropical forests, and in forest regrowth in other areas such as abandoned agricultural lands and managed forests (IPCC, 2007b).

2.1.2. Plantation forests

Plantation forests present a special case for carbon sequestration because they can sequester a proportionately large amount of carbon, whilst the bulk of stored above-ground carbon is removed every few years when new growth occurs. In this scenario, however, the net carbon balance depends to a large extent on the timber use. If it is used in short-life paper products that are burnt or degrade quickly, then no net gains have been made. A net loss in carbon occurs over time if establishing a plantation disturbs soil and results in release of long-held carbon (for example from peat deposits). Whereas, if a plantation is established on a low productive pasture site and is managed for solid wood products, it can sequester much more significant amounts of carbon than the previous land use (Green Peace Policy, 2009).

The fastest way to increase carbon in managed forests on the landscape is to increase the forest rotation age (Sohngen & Brown, 2008 cited by Kula& Gunalay, 2012). Even small increases in forest rotations, when implemented over large areas, could produce measurable increases in carbon stock on the landscape. Given that many of the world's intensively managed plantation forests are managed in rotations, with timber outputs in mind, these landowners could be persuaded to extend their rotations if the carbon price is high enough. Sohngen & Mendelsohn (2003), Murray *et al.* (2004), and Sohngen & Sedjo (2006) all suggest that increases in rotations could be an important component of any carbon policy that values carbon stored on the landscape.

Hoehn & Solberg (1994) argue that in the long run, many additional management strategies can be undertaken to increase total carbon stocks in the forest. Planting forests, rather than relying on natural regeneration after harvest, or forest fire, or other disturbance can increase the rate of carbon accumulation in early years and also the overall quantity of carbon on the site in the long run. According to Sohngen & Brown (2006) shifting forests from one type to another can increase total carbon sequestration across the landscape. This then translates to managed forests offering the opportunity to influence growth rates and full stocking, allowing for more carbon sequestration (Sedjo, 2001).

There are still gaps in understanding of the links between intensively-managed plantations and carbon sequestration, including the quantity and long-term fate of carbon in litter, below-ground tissues and exudates, and soil. Currently there is also a great deal of debate about the long term implications of carbon sequestration and few studies factor in the impact of future climate change on tree growth and carbon sequestration. Some studies suggest that sequestration could be negatively affected by rising carbon dioxide levels in the atmosphere e.g. Oren *et al.,* (2001). It is probably still too early to say for certain what role plantations will be able to play in stabilising climate change in the future, but to understand the intricacies of forest carbon sequestration it is important to measure the amount of carbon captured by plantation forests.

2.2 Forest carbon accounting

Different countries have various views on how to account for carbon sequestered or released from forests. Countries with extensive and expanding forests (e.g., Russia, Canada, Brazil, and the United States) prefer full accounting. "Full Carbon Accounting" can be used to imply complete accounting for changes in carbon stocks across all carbon pools, landscape units and time periods, but can also be referred to as complete accounting of stock changes in all carbon pools related to a given set of landscape units in a given time period. Countries with less forestland (e.g. many European countries) are concerned about the potential to overstate the carbon benefits of forestry management practices and land use changes that enhance carbon sequestration. Countries with high net deforestation rates are also concerned about counting forest sequestration, because it could effectively increase their net emission rated under international agreements (Gorte, 2009).

Kyoto Protocol Articles 3, 6 and 12 are most relevant for forestry. Article 3 states that countries must count both sequestration (storage) and emissions from eligible land use change and forestry activities towards meeting their target commitments. In particular, Articles 3.3, 3.4 and 3.7 provide the framework for the inclusion of sinks in the Protocol. A sink is defined as a pool or reservoir (e.g. a forest) that stores carbon for at least some time, hence lowering the amount of carbon in the atmosphere. In summary the articles deal with the following areas:

- Article 3.3 defines that allowable sinks activities are confined to afforestation, reforestation and deforestation that have taken place since 1 January 1990.
- Article 3.4 stipulates the process for negotiating additional sink activities.

- Article 3.7 permits countries that had net emissions in 1990 from the land use change and forestry sector, to count these emissions towards their 1990 baseline. (UNFCCC, 1998).

For countries with carbon commitments the surest, easiest system for verifying the change in carbon levels is to measure the change in the levels from the beginning to the end of the relevant time period 1990 (the baseline) and 2008-2012 (the Kyoto Protocol commitment period). This is, however, a very slow and expensive approach (Gorte, 2009).

Carbon accounting as defined by the Australian Government, (AGO, 2002), is the process of assessing the amounts of carbon found in different parts of a system. It is needed to estimate the amount of carbon that may be traded or used as an offset against greenhouse gas emissions. Methods of carbon accounting in forests include measuring carbon present in trees, litter and soil, using models to estimate carbon present in forest systems (AGO, 2002).

Field measurement procedures are built on well-established methods used in forestry and ecology, though there is a difference in standards when compared to the standard commercial forestry volume inventory. The emphasis of carbon measurement procedures is on assessing carbon in the whole system (i.e. above-ground biomass including litter and woody debris and below-ground biomass) rather than just the wood volume that is used for products such as saw logs or pulp. The use of models is important to assess the potential of particular areas and species for carbon sequestration projects and to estimate the current amounts of carbon sequestered at particular times in on-going projects. There will always be a need to carry out actual measurements to validate the predictions of simulation models but field measurements are expensive and models can provide a relatively low cost estimate of carbon sequestered in a forest (AGO, 2002).

2.2.1 Carbon stock measurement

The rate of carbon sequestration in forests is related to the growth rate of forests. A young forest, when growing rapidly, can sequester relatively large volumes of additional carbon roughly proportional to the forest's growth in biomass. An old-growth forest acts as a reservoir, holding large volumes of carbon even if it is not experiencing net growth. Thus, a young forest holds less carbon, but it is sequestering additional carbon over time. As a general rule of thumb, approximately half the dry weight of forest biomass is carbon. Carbon sequestration and carbon stock are usually reported on a per hectare basis, and therefore carbon storage in the aboveground biomass is primarily a function of tree size and stocking (Sedjo, 2001).

The simpler of the two principal ways by which the sizes of carbon pools or rates of carbon sequestration are commonly measured, involves measuring the difference in carbon stocks between two points in time. This takes into account conventional forest mensuration methods to measure or model timber volumes, which are then converted to dry weight by reference to tables of wood specific density. The carbon content e.g. 0.5 tC^{-1} is then used to convert dry weight to carbon. These estimates represent quantities of carbon in the stem wood of trees, either standing or harvested as appropriate. In order to account for carbon in non-stem components as well as stem wood, the estimates are increased by a factor known as a “total merchantable” ratio or “expansion factor”. The value of this factor depends greatly on tree species, stand age, management and environmental conditions (Broadmeadow & Matthews, 2003). In this inventory-based accounting system, leaf biomass, ground vegetation and litter are often not included

The carbon content of the soil, although of great importance, has seldom been included because of difficulties in defining and carrying out cost-effective assessments of soil carbon. Moreover, stock changes that may be small in comparison to total soil carbon stocks are difficult to identify, particularly when uncertainties associated with the measurements are considered. An alternative method to account for changes in soil carbon is to combine inventories of carbon in forest vegetation with estimates of soil carbon produced by models of soil carbon dynamics. Depending on the purpose of the inventory, carbon stocks or stock changes in harvested wood products may or may not be assessed (Forestry Research Commission, 2013).

An alternative method of carbon assessment is known as the flux-based approach. This approach measures directly the net flow of carbon into or out of a forest. Technology has been developed, using a measurement technique known as Eddy Correlation so that it is now possible to continuously monitor carbon exchange between all the carbon pools in a forest ecosystem and the atmosphere. The advantage of the flux-based approach is that a net ecosystem flux is measured, accounting for all carbon pools, including dead wood and litter and other fractions, which prove difficult to measure using stock-change methods. The major drawback of the approach is its cost, and thus the small number of flux stations that have been established to date (Forestry Research Commission, 2013).

2.3 Carbon accounting models

According to Matthews (2005) there are more than 30 recognized carbon accounting models and software programmes in use. These models/programmes are applicable to the region or countries where they were designed. Presently South Africa, like so many other developing countries, has not identified a model that it would use nationally for its carbon accounting.

There is abundant literature on the topics of model evaluation, guidelines for application of models in policy settings and standards for model documentation. Prisley & Mortimer (2004) note that, "*If models are to be widely applied in the context of reporting carbon stores and fluxes for greenhouse gas accounting (or for carbon markets), it is reasonable to expect that these models should adhere to scientifically relevant and judicially proven guidelines...*" They outline and discuss eight guidelines for any forest carbon accounting model to adhere to:

- The scope of the model should be clearly defined;
- Models should be clearly documented;
- Models should be scientifically reviewed;
- When possible, model results should be compared with field observations and results of this comparison should be published;
- Sensitivity analysis should be conducted to identify behavior of a model across the range of parameters for which it is to be applied;
- Models should be made available for testing and or evaluation;
- They should be periodically reviewed in light of new knowledge and data; and
- Finally, when models are applied in regulatory or policy development, a public comment period is critical (Prisley & Mortimer, 2004).

While forest carbon accounting is unlikely to attract widespread public interest, interested parties include forest managers, landowners, forest products buyers, and scientists. If and when markets for carbon trading are more firmly established, more parties will become financially involved and interested in mechanics and assumptions of forest carbon accounting models. Consistency and openness in the process of developing models and a well-defined and appropriate context for applying models are crucial in providing a model application that will withstand public scrutiny and legal challenge. When ecological or environmental models are applied in settings with significant policy, economic, regulatory, or social impacts, it is reasonable to hold them to high standards (Prisley & Mortimer, 2004).

2.4 Carbon footprint and sequestration modelling

In terms of carbon accounting it is possible to distinguish between carbon footprint accounting and carbon sequestration accounting. Carbon footprint accounting focuses emissions by a company, organisation or an individual as they carry out their activities while carbon sequestration accounting focuses on the activities or calculations involved in storing carbon in various places or forms.

2.4.1 Carbon footprint models

A carbon footprint by definition is a measure of an individual's contribution to global warming in terms of the amount of greenhouse gases that individuals produced, measured in units of carbon dioxide equivalent (Lynas, 2007). A footprint consists of two parts: the direct or primary footprint is a measure of direct emissions of CO_2 from the burning of fossil fuels including domestic energy consumption and transportation (e.g. car and plane); and the indirect or secondary footprint, which measures CO_2 emissions from the whole lifecycle of products and services used, including those associated with their manufacture and eventual breakdown (Tukker & Jansen, 2006).

Carbon footprint models or calculators are widely available on the Internet but there are no standards or codes of practice associated with these models leading to potentially significant differences and inconsistencies between them. These models or calculators are provided by a range of organizations including government agencies, non-governmental organizations (NGOs) and private companies (Kenny & Gray, 2009).

The major reason companies often pursue carbon footprint projects is to estimate their own contributions to global climate change. Carbon registries and/or greenhouse gas emission estimation protocols help the organisations in defining how much their activities emit as a footprint. The scope of these protocols varies, but estimate direct and indirect emissions as well as emissions from direct energy use. Few organizations are pursuing the broadest scope boundaries including a full range of their supply chain emissions (Matthew*et al.,* 2008).

The biggest and most important problem where sharing carbon footprints responsibility is concerned is that many companies produce many different products, and have a wide supply chain making the sharing of responsibility with their suppliers and consumers a daunting accounting task. Even if this problem can be overcome, many companies would not spend the necessary time and money to understand and calculate this type of footprint. The complexities related to carbon footprint reporting relates to the fact that the original protocols for carbon foot printing were written from a company, instead of a product, perspective. As long as calculating footprints remains voluntary for companies, simplicity must be valued highly in the design of protocols (Matthew *et al.,* 2008).

2.4.2 Carbon sequestration models

The accumulation of carbon by forest stands is often referred to as carbon sequestration. In legal terms, the verb to sequester is defined as to seize temporary possession (of something). This makes a good analogy with the pattern of carbon dynamics, highlighting four important features, which are:

- *"Individual atoms of carbon are continually being exchanged between the atmosphere and a forest stand i.e. an individual atom is only captured from the atmosphere temporarily.*
- *Over the lifetime of a forest stand, more carbon atoms are captured than are released so there is net accumulation of carbon in the forest.*
- *Carbon is only accumulated by a forest up until the point when equilibrium is reached, so that the quantity of carbon accumulated is strictly finite.*
- *The accumulation of carbon by a forest is reversible, with carbon being returned to the atmosphere through dieback, decay and burning of wood if the forest stands are not maintained"* (Broadmeadow & Matthews, 2003).

Kurz *et al.,* (2009), group sequestration models into two categories; empirical yield curves driven models and photosynthesis-driven models. They describe the empirical yield data driven models as, "*similar to the ones that operational foresters use*" in timber supply analysis and forest management planning tools, as they require data on merchantable wood volume as a function of stand type and age. Examples of these models are EFISCEN, (Nabuurs *et al.,* 2000) and CO2FIX, (Masera *et al.,* 2003). On the other hand, photosynthesis-driven models such as 3-PG (Landsberg & Waring, 1997), BIOME-BGC

(Running & Gower, 1991), CENTURY (Metherall *et al.,* 1993) and TEM, (Tian *et al.,* 1999) simulate the response of the forest ecosystem to global change factors. These models are also particularly useful for modelling ecosystem dynamics for which detailed empirical yield data have not been compiled or are not available.

2.5 Carbon calculation software

Liu *et al*. (2008) acknowledged how difficult it was to find a link between software engineering and climate change. Their view is based on software being more about the symbolic virtualized world while environment related issues are more about the natural physical world. Carbon accounting software, often referred to as "Software as a Service" (SaaS), run carbon estimation models in the background and are presented as user interface programmes with little if any access to the model or functions (Buxmann *et al.,* 2008). On the other hand, carbon models require hands-on manipulation of parameters in simple spreadsheet based systems and do not have predefined sets of scenarios.

Kraut & Streeter (1995) pointed out that achieving a successful software system requires tight coordination among the various efforts involved in the software development cycle, which is often impossible to achieve. They further describe many software systems as large and beyond the ability of any individual or small group to create or even to understand in detail. This is largely the case with present carbon estimation softwares that are very complex in most cases.

2.6 Chapter Summary

Carbon models can be divided into those that provide estimates of carbon sequestration, those that estimate a company's carbon footprint and greenhouse gas models (GHG) that combine estimates of all greenhouse gas related emissions, for example methane, nitrous oxide and ozone. Forestry carbon sequestration models can be simplified into those that use yield tables and those that use simulated plant growth. In all cases it is possible to distinguish between models that can be manipulated by the user and software programmes that use carbon models in the background, but that allow limited user inputs. Figure 1 presents a simplified flow diagram of carbon modelling, adopted from Kurz *et al.,* (2009) that will be used in Chapter 3 as a background to the methodology employed in this study.

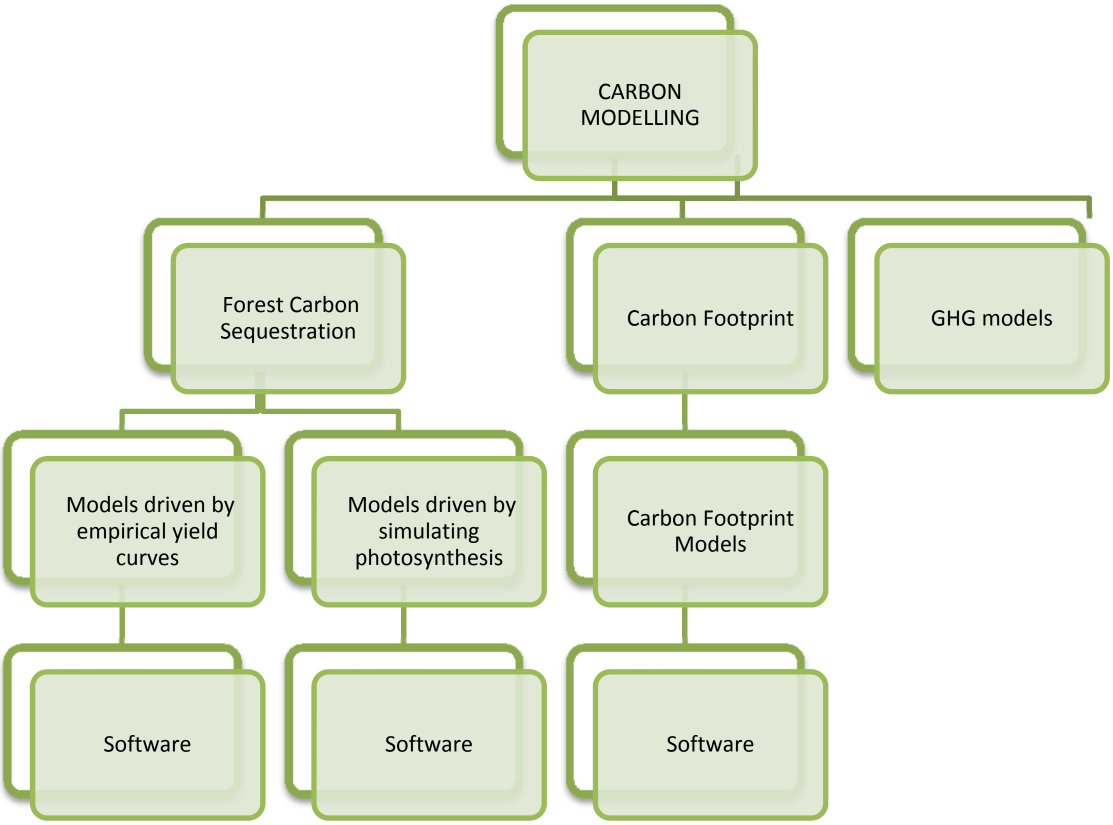

Figure 1: Carbon modelling flow diagram showing the different levels between models and software (adopted from Kurz *et al*, 2009).

Chapter 3: Methodology

3.1 Introduction

A combination of quantitative and qualitative approaches to data collection was followed within this research. Studies using this approach generate both numerical and narrative data (Tashakkori & Teddlie, 1998). The qualitative data served a descriptive purpose to obtain an insight into the South African Forestry Industry's perceptions on carbon modelling (Babbie & Mouton, 2001) and the quantitative to test the accuracy in prediction of the identified models. The following activities took place as part of this study and will be discussed separately:

- Literature search to identify potential international carbon models and computer programmes.
- First level selection of internationally available models and programmes.
- Key informant questionnaire survey in the South African Forestry Industry to determine carbon model requirements and to gather information about the carbon estimation *status quo* in SA.
- Development of a multi criteria decision framework (based on survey responses) to evaluate the selected models and programmes.
- Enumeration of the NCT Enon plantation and estimation of the carbon stock from this plantation based on Dovey (2009) biomass expansion functions.
- Parameterization of the most preferred carbon models and comparison with the Dovey (2009) biomass expansion functions.

3.2. Literature search to identify potential international carbon models and computer programmes

Generally accessible websites such as www.ieabioenergy-task38.org ,www.cifor.org, and www.wikipedia.org were consulted as a starting point to identify models and programmes that are discussed in the public domain. This search was complimented with a more detailed literature search of scholarly articles regarding carbon models and carbon calculators. (Matthews, 2005; Matthews *et al.,* 2008; CIFOR, 2009.).

Different models and software programmes were drawn from literature and internet searches. These models were then selected for comparison on the basis of the following criteria used by Kenny & Gray (2009):

(i) Complexity and relevance.
(ii) Reliability: The model had to be developed by an expert team or organization.
(iii) Recommendation: Models had to be recommended by a Government Department or an organization in the Forestry Industry.

Where possible, carbon model and programme designers were also contacted via e-mail to ask for more information about their models and/or programmes. They were also asked if they would be interested in assisting with guidance whilst their model/ programme was tested for use in South Africa.

3.3. First level selection of internationally available models and programmes

More than 30 models were identified during the initial literature survey (see section 4.2). The availability of models and software vary from freely available to very restricted access at a high consulting or software fee. Part of the exercise was, however, to identify models and software that are potentially useful and applicable to South African conditions. This called for a selection of the more applicable models that could be included in a questionnaire survey to key informants in the South African Forestry Industry. There was a need to have a shorter and manageable list for purposes of obtaining feedback from respondents as a longer list might have led to not receiving any feedback at all. De Vaus (2002) explains how the length of the questionnaire can impact response rates. A questionnaire that is too short may make the survey seem insignificant, while a long questionnaire might intimidate respondents.

The following criteria were used to filter the initial list of models and software to a more manageable list that was included in the questionnaire survey:

1. Is the model/software freely available;

2. Relevance to the forestry industry and could cater for biological carbon sequestration;
3. Possible to adjust to South African plantation conditions (adjust for biophysical conditions as well as tree parameters);
4. Have some form of developer support (not a pre-requisite but desirable).

Based on literature descriptions of what each model/software comprises of and requires as input information, models and software were tested against the above mentioned criteria. Models and software that were not at all applicable to forestry conditions were removed from the list, while models/software with relevance to forestry or having any forestry or biomass calculation component were given priority in selecting or shortlisting for inclusion in the survey to Industry stakeholders. Most software programmes fell out during this selection as they are either not freely available (quite often very expensive) or suitable to South African conditions (closed systems not adjustable to SA conditions).

3.4. Questionnaire survey in the South African Forestry Industry

3.4.1 Identification of sampling population

A stakeholder analysis can be used to identify stakeholders that will be either positively or negatively influenced by a project or, in this instance, a decision (UNICEF&MSH, 1998). It was necessary for purposes of the study to narrow down and define who the stakeholders were as the carbon modelling field is new and growing. This would also help in generating relevant information. A stakeholder analysis was performed to identify the stakeholders in the forestry industry (Babbie & Mouton, 2001). Stakeholders were defined as the interest groups that are involved in the management and utilization of carbon forestry modelling in the South African Forestry Industry. They form a diverse group from technical assistants to managers and planning officers who use and design the models in use for calculating and or estimating carbon quantities in trees.

An initial population of 20 informants was identified for the survey. They were asked to identify other informants who might be interested in the topic. Through this snowball sampling process (Babbie & Mouton, 2001; Explorable, 2013) it was possible to identify an additional 12 informants. This group of 32 informants formed the sampling population for this study (Babbie & Mouton, 2001) and represented nearly every forestry company, industry body and research institution in South Africa (See Appendix A for list of institutions represented by the survey). This study was not intended to be representative of a large sample population such as "all foresters in South Africa", but rather a key informant study (Babbie & Mouton, 2001) of people who might be directly involved in carbon estimation in the forestry industry in South Africa.

3.4.2 Development of a questionnaire

A questionnaire was developed for the identified stakeholders. Although the use of questionnaires is usually seen as a quantitative method (Alreck & Settle, 2004), the questionnaire consisted of both closed and open ended questions, resulting in answers that could be quantified numerically, and others used for descriptive purposes.

Aspects such as simplicity of the language, length of questions, leading and negative questions, ambiguity and detail of questions were considered (De Vaus, 2002). Where closed-ended questions were used, care was taken to ensure that response categories would be exhaustive and mutually exclusive and that respondents had the opportunity to add to the categories (Babbie & Mouton, 2001).

Before questions were formulated the different research issues were identified with knowledge of the kind of data necessary to study these issues (Bless & Higson-Smith, 1995). These issues were identified as:

- The need for carbon models/tools in South Africa ;
- Forest carbon model qualities,
- Knowledge of existing forest carbon models and their use in SA.

Questions were formulated and presented in sections according to these three research issues. The last section of the questionnaire gave the respondents room to add their personal views regarding carbon modelling in general (See Appendix B).

The research questionnaire was tested among student peers for comments and feedback before being sent to the survey population. This step is recommended by Babbie and Mouton (2001) as it reduces the possibility of errors. Where the questions were rendered ambiguous or not clear by peers, the questionnaire was altered and necessary changes made.

3.4.3 Questionnaire survey

The questionnaire and survey design were approved by the Stellenbosch Research Ethics Committee and sent out via e-mail as a formatted e-mail attachment to respondents (De Vaus, 2002). The questionnaire document contained a covering letter explaining the aim of the survey, its importance and an assurance of confidentiality (Robson, 2002). It also encouraged replies by allowing respondents to e-mail or fax the completed questionnaires and promised a copy of the research results to respondents who would return the questionnaire. The respondents were also invited to consult directly with the researcher if they had further questions.

A period of 6-8 weeks was set aside to allow for feedback from respondents, after which it was determined that there was a willingness to participate and support for the survey, but that the people were too busy to complete the questionnaires. When follow-ups were made, the respondents indicated that they would complete the questionnaire in due course but then failed to submit it. Follow-ups are subjected to the law of diminishing returns and it is recognised that the longer a respondent delays replying, the less likely he or she will be to do so (Babbie & Mouton, 2001). Therefore no further reminders were sent and it was assumed that no more questionnaires would be received after the said period. It was then concluded that there was no significant bias between respondents and non-respondents except for time and work pressure.

The questionnaire was sent to the 32 key informants, of which 13 filled out and returned the questionnaire. This presented a 40% response rate which is acceptable for such a small sampling population (Hetherington, 1975 in Turyahabwe, 2006). Babbie and Mouton (2001) define a representative sample as "*...representative of the population from which it is selected if the aggregate characteristics of the sample closely approximate those same aggregate characteristics in the population*". An analysis of respondents did indicate that within the 40% sample the respondents were representative of forestry company managers and planners, researchers and institutional bodies.

3.5 Development of a multi criteria decision framework

A multi-criteria approach was used in identifying and select the models to be used. Multi-Criteria Analysis (MCA) is a decision-making tool developed for complex problems. In a situation where multiple criteria are involved confusion can arise if a logical, well-structured decision-making process is not followed. The main role of the technique is to deal with the difficulties that human decision-makers have when handling large amounts of complex information in a consistent way. MCA techniques can be used to identify a single most preferred option, to rank options, to short-list a limited number of options for subsequent detailed appraisal, or simply to distinguish acceptable from unacceptable possibilities (Dodgson, *et al.,* 2009).

Attributes of MCA deemed appropriate and useful for this study were its capability to work with mixed data, where analysis need not be data intensive and allows the incorporation of both qualitative and quantitative information and its permission to directly involve multiple experts, interest groups and stakeholders (Mendoza and Prabhu, 2005).

All MCA approaches make the options and their contribution to the different criteria explicit, and all require the exercise of judgment though they differ in how they combine the data (European aid, 2013). In the questionnaire survey respondents were asked to rank a set of carbon model qualities based on a ranking system within a scoring range of 1-5: 5 -“Very important”, 4 -“Important”,3 - “Maybe”, 2- “Not necessary” and 1 - “Not sure”. The qualities included:

- Highly accurate;
- User friendliness;
- Species specific;
- Suitability for all commercial species in South Africa;
- Ease in modification of different scenarios;
- Estimation of above ground carbon;
- Estimation of below ground carbon;
- Includes/encompasses all regions in South Africa;
- Simplicity in result interpretation;
- Easy to use;
- Technical complexity; and
- Ease of determining input variables.

The responses from the questionnaire survey was aggregated and used to assign an importance weighting to each of the model qualities.

The models selected and included in the questionnaire survey were then evaluated by the researcher. Each of the models was tested based on the preferred qualities listed above. A Likert scale rating of 1 to 5 where 5 was “agree strongly”, 4 “agree”, 3 “disagree”, 2 “strongly disagree” and 1 “not sure” for each of the identified ‘preferred qualities’ was assigned by the researcher. Likert scales are a non-comparative scaling technique and are one-dimensional (only measure a single trait) in nature. They can be defined as, “*A psychometric response scale primarily used in questionnaires to obtain participant’s preferences or degree of agreement with a statement or set of statements*” (Bertram 2009).

Decision making to reach a general consensus can be very difficult to achieve. By using MCA the survey respondents and the researcher do not have to agree on the relative importance of the criteria or the rankings of the alternatives. Each entered his or her own judgments and made a distinct, identifiable contribution to a jointly reached conclusion (Mendoza *et al.,* 1999).

Several methods for the aggregation of judgements can be developed, e.g. the weighted sum method, the weighted sum product and the outranking method. The sum product method was used for making calculations (European aid, 2013) where the total rating for each model consisted of the sum of survey respondent weightings multiplied with the Likert scale rating of the researcher for every model quality assessed:

Total rating per model = Σ (survey respondents’ weighting x researcher Likert scale rating for each model quality).

The Multi Criteria Evaluation was thus a combination of stakeholder preferences and researcher evaluation and made it possible to rate the models identified in section 3.3 from most to least preferred.

3.6 Carbon stock assessment of the NCT Enon plantation

The 1197.5ha NCT Enon plantation was selected to test the carbon models against real world data. This plantation was selected as part of a larger environmental services Green Landscapes project by the Department of Forest and Wood Science, Stellenbosch University.

Enon plantation is located outside the town of Richmond in KwaZulu-Natal around the longitude 29°48'38.14"S and latitude 30°13'33.14"E.

Quantum Geographic Information System (QGIS, 2011) 1.7 was used to create a map of the NCT Enon plantation for enumeration purposes. A 200m by 200m systematic grid was laid over the map of Enon for sampling, and from this grid sample plots were randomly selected using the randomised vector function in QGIS (Figure 2). Stratification was done for species and for age (forming age classes). Enon plantation has the following species*: Pinus patula* (1.9ha), *Eucalyptus smithii* (568.4ha), *Eucalyptus saligna* (12.1ha), *Eucalyptus grandis* (71.8), *Acacia mearnsii* (258.8ha), and *Eucalyptus dunnii* (9.7 ha). *E. smithii* covers 61% of Enon plantation. Compartments were allocated to four age class categories (1-3 years, 4-6years, 7-9 years and above 10 years) to cater for the change in Diameter at Breast Height (DBH) across the age range.

Circular plots with a 10 m radius were laid out using systematic random sampling. In total, 119 sample plots were taken from all ages for *E. smithii* alone. A total of 5466 trees were sampled. Enon plantation practices a coppicing system and in order to have a good estimate of the above ground volume estimate, 3cm was used as the smallest DBH in order to account for all tree stems. Plots positions were predetermined using QGIS, and a Global Positioning System (GPS) was used to find these plots in field.

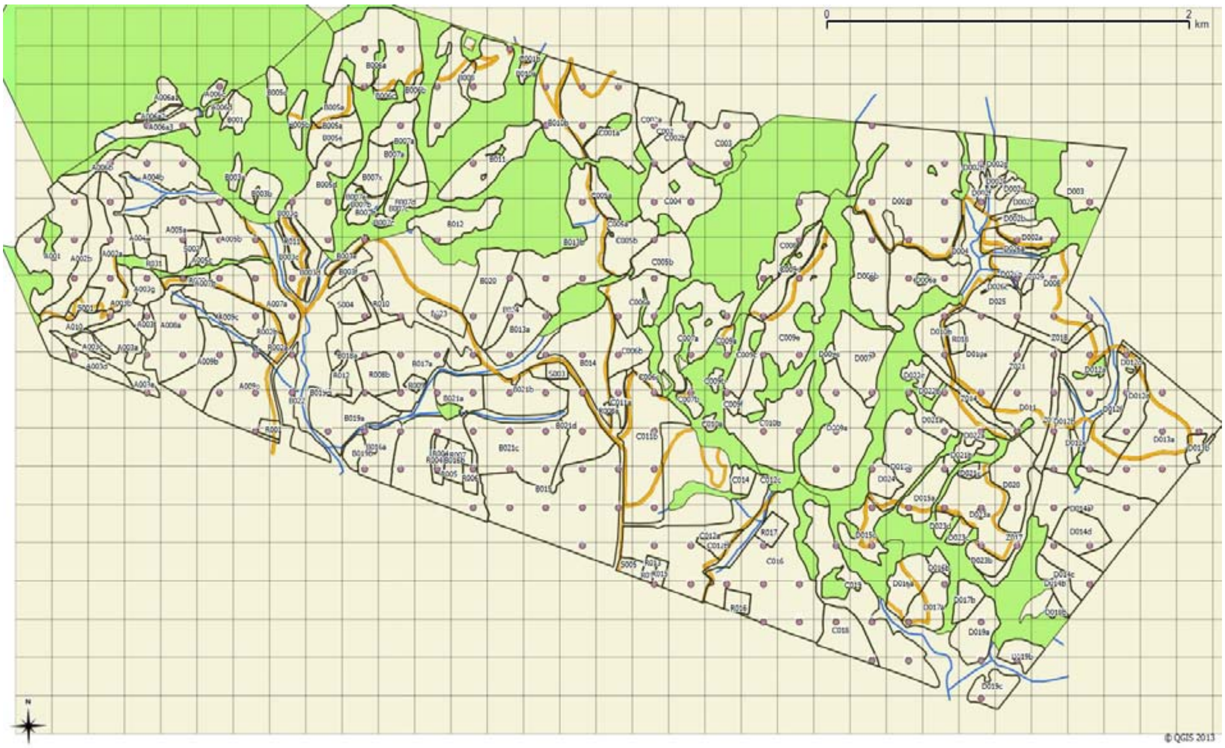

Figure 2: Map of Enon showing the 200m grid (QGIS, 2011)

Conventional methods of measuring biomass values in the field are so far the most accurate and reliable method for estimating above ground biomass, although they are often time consuming, labour demanding and cannot cover spatial distribution of biomass in larger areas (Houghton, 2005). Biomass can be estimated by destructive and non-destructive means in field based surveys. The destructive method is to fell a specific number of sample trees across their age distribution within the geographic area where knowledge of biomass is required. These trees are weighed to develop a biomass equation. This is, however, a very time consuming and not always practical way of estimating biomass (Brown, 1997). In non-destructive methods, regression equations are developed (Foody *et al.,* 2003) based on data from previously felled trees (outside the sample area) using some easily measurable dimension such as diameter (Brown, 1997). Biomass and trunk diameter are highly correlated and therefore regression models can be used that convert trunk diameter data to biomass data. Allometric equations that relate biomass of several tree components to DBH are used to calculate biomass values. Other variables such as height can also be used in regression equations (Brown, 1997).

In this study, destructive sampling was not possible as the plantation owner did not grant permission for felling trees. It was also deemed outside the scope of the study as the main objective was to compare internationally available carbon models with South African biomass functions. Merchantable tree volume/ha was calculated for each species per age class according to the method described by Bredenkamp (2000).

The merchantable volume per species per age class was used in the calculation of above ground biomass through the use of biomass expansion functions (BEF) developed by Dovey (2009) for South African plantation species (Table 1). Biomass expansion functions serve as multipliers to convert timber volume to biomass and are widely applied in tropical and subtropical regions (see for instance Brown *et al.,* 1989; Chhabra *et al.,* 2002).

The BEF developed by Dovey (2009) are fairly recent and are currently used in South Africa (see for example Ackerman *et al.,* 2012). More importantly they cover a wide range of species that include *E. smithii.* It should be noted that expansion factors linked to the stem volume are constrained to the use within the same silvicultural treatment of the parameterisation data. They are not particularly suited to adapt to changes in the relationship between stem volume and aboveground tree biomass (Ackerman *et al.,* 2012), but the planting espaceement and silvicultural treatment at Enon plantation fall within South Africa and Swaziland regimes described by Dovey (2009).

Considering that *E. smithii* represents 61% of the Enon plantation area, a decision was made to use it as the species of choice in the study as it offered a broad diameter range and was available for all age groups selected before going to the plantation.

Table 1: Multipliers to convert timber volume to dry mass (t m^{-3}; A), and timber dry mass to bark (t ha^{-1}; B) and branch mass (t ha^{-1}; C) (Dovey, 2009)

Biomass estimation			
Species	A (t m^{-3})	B (t ha^{-1})	C (t ha^{-1})
Pine: *P.patula*	0.387	0.09	0.26
Wattle:*A.mearnsii*	0.654	0.13	0.26
Grandis: *E.grandis*	0.450	0.12	0.12
Hardgums: Average for *E. dunnii, E. macarthurii, E. nitens and E. smithii*	0.549	0.13	0.22
E.dunnii	0.536	0.16	0.12
E.macarthurii	0.551	0.15	0.21
E.nitens	0.526	0.12	0.34
E.smithii	0.581	0.10	0.21

To calculate the stem wood biomass for 100 m^3 of *E. smithii* timber, for example, one multiplies the volume by 0.581 (column A in Table 3), yielding 58.10 t ha^{-1} of volume as dry wood. The branch and bark estimates are calculated by multiplying the 58.10 t ha^{-1} by 0.1 (column B) for branches and 0.21 (column C) for bark. The results, 5.81 t ha^{-1} and 12.2 t ha^{-1} are then summed up to give a total biomass volume. The biomass volume can be converted to carbon by using a conversion factor of 0.5 g C/g dry matter following procedures by Matthews (1993) and Lamlom and Savidge (2003). The carbon value for 100 m^3 of *E.smithii* this is then found to be 38.1 tons.

3.7 Parameterization of the most preferred carbon models and comparison with the Dovey (2009) biomass expansion factors

After deciding on which models were to be tested for Enon, it was important to parameterise them. Simple paramerisation guidelines from Li (2005) were used to adapt the selected models to South African conditions. The most important element of the parameterization process was to adjust the selected models to South African timber species (*E. smithii* in particular) and their growth rates. The selected models use yield table inputs to calculate accumulated carbon over time in a plantation. They have built in values for density and other parameters as well as root and underground carbon calculations. After consultation with the designers of the models it was decided to use the yield tables of Kotze *et al.* (2012) for parameterisation. The models were also adjusted for average temperature and rainfall.

As a way of testing the models, the yield table data from Kotze *et al.* (2012) was also used to estimate the cumulative amount of carbon per year for a low (site index 14), medium (site index 18) and high (site index 22) quality site with the Dovey (2009) biomass expansion factors.

3.8 Statistical Analyses

The data and information from the questionnaires were imported into Microsoft Excel worksheets (Microsoft, 2010). This involved coding, grouping and ranking of answers to allow for analysis. Descriptive data analysis was conducted within Excel. No statistical analysis was performed on the MCA framework as it provided a simple ranking system.

In terms of model comparison the following statistical procedures were employed:

3.8.1 Comparing model outputs against carbon estimates from yield table data

The Dovey (2009) biomass expansion functions were applied to *E.smithii* yield table data for low, medium and high site index sites to estimate the cumulative amount of carbon per year for a 15 year rotation. Carbon data output from the selected models was compared for every year of the rotation against the yield table data for the three site conditions.

The Student t-Test (Bonferroni test) for comparisons of means was used in determining if there is a significant difference between the models and the yield table outputs when Dovey (2009) functions were used (Clewer & Scarisbrick, 2001). The models are deterministic in nature; hence give only one value per given year as an output.

The relationship between the model outputs and the best, good and poor siteswere described using scatterplots with correlation coefficients.

3.8.2 Comparing model output against carbon estimates from Enon

The selected models were used to generate carbon estimates per hectare for *E. smithii* at ages 3, 6, 9 and 14. This was compared to the actual carbon field estimates based on the enumeration data from Enon and the Dovey (2009) biomass expansion functions.

Mean squared error (MSE) is arguably the most important criterion used to evaluate the performance of a predictor or an estimator. This was used to test for accuracy of the models on Enon plantation. The predictor with the smaller MSE is the more accurate (SAS, 2013).

The student T test was also carried out to see if there was any significant difference in the models and Enon plantation for the period the data was collected.

SAS enterprise guide software 9.2, (SAS, 2013) was used in analysing the data and Statistica version 11.4, (Statsoft Inc., 2013) was used in generating scatterplots for easy relationship visualisation in the attempt to show how much one variable is affected by another. Formula for MSE calculations were done in Excel (Microsoft, 2010).

3.9 Chapter Summary

This chapter presents a background on the identification of plantation stakeholders and the process involved in the selection of the models to be tested and how they were identified and arrived at. It details the methodology approach used to collect the data, and how the data was analysed. In Chapter 4 the results of the data collection is presented.

Chapter 4: Results

4.1 Introduction

This chapter presents the results according to the research questions and is outlined in line with the study objectives. It presents an in-depth view of the results and further explains how the preferred qualities were used in determining which models to test in the study. The models are briefly discussed in detail before the comparisons between the models and carbon estimates form yield tables and Enon plantation.

4.2Identification and first level selection of carbon software and models for further evaluation

More than 30 models and software programmes were selected from the initial literature survey. Table 2 presents the list and description of the models and software that were identified. It must be noted that the models in Table 2 were available in 2013 but that there might be other models, but not generally available in the public domain as of November 2013.

Table 2: Models and software identified in 2013

Name	**Description and source**	**Model and software type**
3 PG	A stand level model for simulating forest growth. It is a generalized forest carbon allocation model, published by Landsberg & Waring (1997) that works with any forest biome and can be run as an Excel spreadsheet by practicing foresters. Requires Stand age, Stocking, Foliage Dry Matter (DM) Root DM, Stem DM, Stand volume, Leaf Area Index (LAI), Mean Annual Increment (MAI), Mean DBH, Basal area and Total litter (Landsberg & Waring, 1997).	**Carbon sequestration model**
Access Dimensions	Carbon accounting tool within mid-market financial management software. Solutions available based on request and nature of problem. Calculates footprint of organisations. Available at www.theaccessgroup.com (Accessgroup, n.d.)	**Carbon footprint software**
BIOMETRE	BIOMITRE is a standard, user-friendly software tool that can be used to analyse GHG balances and cost-effectiveness of different biomass energy technologies. The main purpose of BIOMITRE is to unify methodologies into a standard approach for evaluating the GHG balances and cost-effectiveness of GHG savings associated with biomass technologies (Dam *et al.,* 2004).	**Carbon sequestration software**
Brighter Planet's Carbon Middleware	All calculations include live methodology statements and the calculation models themselves are open source. Calculates Carbon footprints of individuals or organisations. Available at www.brighterplanet.com and www.ghgprotocol.org(Brighter planet, n.d.; GHG Protocol, n.d.)	**Carbon footprint software**
CAMFor	Carbon accounting model for forests. It has been created to perform carbon accounting both at stand (or project) level and at estate (or landscape) scale. CAMFor finds much of its origin in the CO2 Fix model. A detailed description is found in the CAMFor manual by Richards & Evans, (2000). CAMFor was designed for Australian carbon accounting. Input requirements are, biomass (stem wood, branches, bark, fine and coarse roots, leaves and twigs) soil (organic matter and inert charcoal) Debris (coarse and fine litter, slash, below	**Carbon sequestration model**

Name	Description and source	Model and software type
	ground dead material) Products (waste wood, sawn timber, paper, biofuel, reconstituted wood products) (Richards & Evans, 2000).	
CAMSAT	Carbon management self-assessment tool, for companies to measure their offset. The tool consists of a series of 23 multiple-choice questions, the result of which is one overall score and a synopsis of suggestions for ways in which carbon management can be improved in relation to the risks and opportunities identified. (Bioenergy Task38, 2013).	**Carbon footprint model**
CapISA SPM	CapISA Sustainability Performance Management (CapISA SPM) is a software package developed by Capiotech and the ISA (Integrated Sustainability Analysis) team at University of Sydney. (Bioenergy Task38, 2013).	**Carbon footprint software**
Carbon Calculated	Carbon management and accounting solutions that meet regulatory compliance and industry standards, along with a platform of emissions data with sources and guidance for consultants. Calculates sustainable carbon footprints. Available at www.carboncalculated.co.za(Carbon calculated, n.d.)	**Carbon footprint software**
Carbon Guerrilla.	Software as a Service (SaaS) based Carbon Accounting and Business Management tool covering voluntary or compliance based schemes. An agreed fee of €65 per hour, minimum is payable to use the programme. Available at www.computatis.com.(Computatis, n.d.)	**Carbon footprint software**
CarbonLow Emissions.	Carbon measurement software for businesses to measure their emissions. Offers the integrated Carbon Accounting and Trading Solution, (iCAT),an online software which collects company or organisational data. Property of CarbonLow. Available at www.carbonlowemissions.co.uk.(CarbonLow, n.d.)	**Carbon footprint software**
Carbon View.	Carbon management and accounting platform for enterprises, supply chains and government. The software has been developed to assist organizations to understand the impact that their operations have on the environment by measuring, monitoring and mitigating their carbon emissions. Available at www.carbonview.com(Carbon View, n.d.)	**Carbon footprint software**

Name	**Description and source**	**Model and software type**
Carbonetworks.	Established enterprise level carbon accounting software, run as an internet accessible service. UK, online calculations. Needs access rights at a fee. Available at www.carbon-networks.com(Carbon Networks, n.d.)	**Carbon footprint software**
CASMOFOR	CASMOFOR:-CArbon Sequestration MOdel for FORestations is an accounting model to assess the removals and emissions of carbon in afforestations. It requires forest inventory data, existing soil profile data and historical (or projected) data on stand-replacing disturbances (fire, insect and harvesting)(Somogyi, 2011, CASMOFOR, 2013).	**Carbon sequestration model**
CBM-CFS3	Operational-Scale Carbon Budget Model of the Canadian Forest Sector; The CBM-CFS3 is a yield data driven model with explicit simulation of dead organic matter. Growth curves, derived from forest inventory data, describe the accumulation of biomass carbon in vegetation (above and below ground) in each forest ecosystem type, Uses default IPCC values where densities are unavailable (Kurz *et al.,* 2009).	**Carbon sequestration model**
CFIX	C-Fix is a Monteith type parametric model driven by temperature, radiation and fraction of Absorbed Photosynthetically Active Radiation (fAPAR), the last variable derived by processing NOAA/AVHRR data of 1997 acquired over Europe as well as VEGETATION (VGT) data for the same region for the period 1998–1999 (Veroustraete, *et al.,* 2002).	**Carbon sequestration model**
CO2FIX	One of the oldest carbon accounting applications available. It consider Stand age, Stocking, Foliage Dry Matter (DM), Root DM, Stem DM, Stand volume, LAI, MAI, Mean DBH, Basal area and Total litter (Mohren *et al.,* 1999).	**Carbon sequestration model**
Ecometrica Our Impacts	SaaS-based, Carbon Disclosure Project (CDP)-accredited greenhouse gas accounting software for all three Green House Gas (GHG) scopes. Sustainability management software service, accredited by the CDP. Available at www.ecometrica.com (Econometrica, n.d.)	**Carbon footprint software**

Name	**Description and source**	**Model and software type**
EPS Corp	Encompasses Scopes[1] 1, 2 and 3 carbon accounting and energy management platform for manufacturers. Monitors and reports on scopes 1, 2 &3. Also known as AMERESCO INTELLIGENT SYSTEMS. Available at www.epsway.com (EPS Corp, n.d.)	**Carbon footprint software**
FICAT	Forestry Industry Carbon Assessment Tool. It considers Carbon in products and all related emissions, from "cradle to the grave". Available at www.ficatmodel.org(FICAT,2013)	**Carbon footprint and sequestration model**
First Carbon Solutions	Carbon management accounting application for global industry, supply chains and governments. Improves organisations' reporting in the Carbon Disclosure Project. It belongs to a consulting company. Available at www.firstcarbonsolutions.com(First Carbon Solutions, n.d.)	**Carbon footprint software**
FVS	Forest Vegetation Simulator, was developed by the US Forest Service, includes a carbon accounting model. Requires details of Stand Information, Stand ID, Location code, Stand origin year, slope, Aspect, Elevation, Plant Association, site species, site index, inventory year, inventory/Cruise design and grouping codes. Also tree information such as plot number tree number, tree count, tree history, species, DBH, height, crown ratio, damage/severity codes, tree value class, cut/leave status and growth increment (USDA, 2013).	**Carbon footprint and sequestration model**
FoundationFootprint	A web based (SaaS) carbon calculator, accounts for energy, water and supply chain emissions management system based on international standards for managing the environment protocol standards. Offers solutions on how to estimate and analyze organizations' footprints. Available at www.foundationfootprint.com (Foundation Footprint, n.d.)	**Carbon footprint software**

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[1] The GHG Protocol Corporate Standard classifies a company's GHG emissions into three 'scopes'. Scope 1 emissions are direct emissions from owned or controlled sources. Scope 2 emissions are indirect emissions from the generation of purchased energy. Scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions (Ghgprotocol, 2013).

Name	**Description and source**	**Model and software type**
GaBi Software	Software provided by PE International for Corporate Carbon Footprint calculations. Product Life Cycle assessment engine available at a fee. Available at www.gabi-software.com(GaBi Software, n.d.)	**Carbon footprint software**
GEMIS	Global emission model for integrated systems. (GEMIS) consists of an analysis model to determine energy and material flows (including transports). Available at www.iinas.org and www.ghgprotocol.org(Iinas, n.d.; GHG Protocol, n.d.)	**Carbon sequestration model**
GORCAM	Graz / Oak Ridge carbon accounting model, is an Excel spreadsheet model that has been developed to calculate the net fluxes of carbon to and from the atmosphere. Requires Stand age, Stocking, Foliage Dry Matter (DM), Root DM, Stem DM, Stand volume, Mean DBH, Basal area and Total litter(Ecobas, 2013).	**Carbon sequestration model**
HWP	Harvested Wood Products (HWP) dead wood carbon assessment. Carbon stocks of harvested wood products in use and in solid waste disposal sites (SWDS) of a given country (Bioenergy Task38, 2013).	**Carbon sequestration model**
LEAP:	Long range Energy Alternatives Planning System, a software tool for energy planning and greenhouse gas mitigation analysis. It is used for energy policy analysis and climate change mitigation assessment (Stockholm Environment Institute). Available at www.energycommunity.org(Energy Community, n.d.)	**Carbon footprint software**
ManageCO2.	A Carbon Accounting and Management Reporting Software, provided by manageco2 without consultancy services. Available from www.manageco2.com(Manage Co2, n.d.)	**Carbon footprint software**
Nootrol	Carbon accounting software for large corporates to manage emissions within their supply chain. Provides regular, accurate information on sustainability achievements and progress. Available at a fee from Footprint Software. Ireland. Available at www.nootrol.com(Nootrol, n.d.)	**Carbon footprint software**
SIMAPRO	Life cycle assessment (LCA) based on various accounting systems and that allows different	**Carbon footprint software**

Name	Description and source	Model and software type
	types outputs. Sustainability Life Cycle Assessment carbon Footprint. Available at www.simapro.co.uk (Simapro, n.d.)	
SoFi Software	Software provided by PE International for Corporate Carbon Footprint calculations. SoFi assists in Carbon Disclosure Project (CDP) reporting for companies. Available at www.sofi-software.com(SoFi Software, n.d.)	**Carbon footprint software**
TEAM Sigma	Global enterprise energy/carbon management package provided by TEAM Energy Auditing Agency Ltd. Available at www.teamenergy.com(Team Sigma, n.d.)	**Carbon footprint software**
TimberCAM	TimberCAM is a carbon accounting model that tracks the fate of carbon stored in wood products through their life cycle. The calculator computes the carbon in the residues created in all stages of the life cycle of the product. It includes carbon stored in products, as well as the carbon that is not emitted into the atmosphere by using redundant products or residues instead of fossil fuels (Greenbiz, 2013).	**Carbon footprint and sequestration model**
TRIRIGA TREES IBM	IBM software, designed to reduce energy consumption and meet sustainability goals. Price range from US$ 7,000-22,000.Available at www.ibm.com(IBM, n.d.)	**Carbon footprint software**
Verteego Carbon	Carbon Inventory, Accounting, Management and Reporting Enterprise Software. Allows an Organisation to measure environmental impacts, measure carbon and energy consumption, environmental footprint. Available at www.verteego.com(Verteego Carbon, n.d.)	**Carbon footprint software**

Based on the first level selection process (as described in section 3.3) Table 2 was reduced to 12 models, which were eventually included in the questionnaire survey. These models are presented in Table 3 together with the selection criteria employed in evaluating the models and software from Table 2.

Table 3: Models included in the questionnaire

Model	**Criteria**			
	Is the model freely available?	Is it relevant to the forestry industry and could it cater for biological carbon sequestration?	Is it possible to adjust to South African plantation conditions?(adjust for biophysical conditions as well as tree parameters)	Will some form of developer support be available? (Not a pre-requisite but desirable).
CASMOFOR	Yes	Yes	Yes	Yes
CBM-CFS 3	Yes	Yes	Yes	Probably, trainings available
3 PG	Yes	Yes	Requires photosynthetic information	Not sure
FICAT	Yes	Yes	Yes	Not sure
C02 FIX	Yes/ On request	Yes	Have to redesign model	None
GORCAM	Yes	Yes	Possible	One of the developers passed away, currently not available
CAMFor	Yes	Yes	Yes	Not sure
GEMIS	Yes	Yes	Not sure	Not sure
TIMBERCAM	On request	Yes	Not sure	Not sure
C FIX	On request	Yes	Have to redesign model	Not sure
HWP	On request	Yes	Yes	None
CAMSAT	On request	Yes	Yes	None

The models in Table 3 are freely available, have a relevance to forestry and are described as being possible to adjust to South African forestry plantation conditions.

4.2 Questionnaire survey

4.2.1 Relevance of carbon models/tools in South Africa

The very first question to answer in this study was if there is a need for a South African carbon model. The majority of respondents in the questionnaire survey (77%) agreed that there is such a need. The remaining 23% were of the opinion that the Forest Industry Carbon Assessment Tool (FICAT) should be adopted as it fits the Industry's needs. FICAT is a carbon footprint model developed by the National Council for Air and Stream Improvement (NCASI) an independent, non-profit research institute that focuses on environmental and sustainability topics relevant to forest management and the manufacture of forest products in the USA. Its adoption in the South African Forestry Industry is currently driven by the Paper Manufacturers Association of South Africa (PAMSA) and Forestry South Africa (FSA).

The reasons cited for choosing the model over any that's currently available was that, since the model is now being used by pulp and paper producers around the world, South Africa as a paper and pulp producing country can adopt it. Apart from this the industry considers FICAT an encompassing model as it considers what happens to the carbon outside the plantations.

Some respondents supported the need for a consolidated report on tools and methodologies as they shared the sentiment that there are presently a lot of "smokes and mirrors" with regards to carbon monitoring, verification and reporting. Of importance to others is a need to get clarity on measurement of soil carbon.

The different stakeholders had various reasons why they needed a carbon model. Listed below is a summary of their responses:

1. Important for carbon sequestration calculation to be able to estimate emissions and the quantification of the forestry industry's environmental impact;
2. As a potential future requirement for carbon taxes and carbon credits (data gathering);
3. Forestry Stewardship Council (FSC) certification in future will come with carbon estimates as a requirement;
4. To better prepare the country for carbon trading and auditing;
5. Being able to determine carbon in the soil in a universally acceptable procedure or methodology; and
6. As a response to the National Climate Response Policy.

4.2.2 Current methodology for measuring carbon in the industry

Respondents who have used carbon models in the past cited the CAMFor and CBM CFS 2 models but indicated that they were not satisfied with them. Other methods used included:

- Global Reporting initiative guidelines.
- Dovey (2009) allometric equations.
- REDD+ guidelines.
- Process based models (not specified).
- Forestry Industry Carbon Assessment Tool.
- Food and Agriculture Organization's procedures on Forest Resource Assessment.
- Total soil carbon determination (Laboratory related).
- Spatial extrapolation from field sampling.
- Allometric expansion factors.
- In house inventory (tree volume records converted to carbon amounts).

From the survey it was thus possible to deduct a need for carbon assessment methodology. It was therefore important to understand what the preferred qualities for a preferred model should be.

4.2.3 Preferred qualities in a model

Respondents were asked to rate the possible qualities that a good carbon model should have on a scale of one to five (5 -"Very important", 4 -"Important", 3 - "Maybe", 2- "Not necessary" and 1 - "Not sure".). The percentage of respondents (n = 13) per rating category was estimated and is presented in Table 4. Qualities such as above ground carbon were indicated by most respondents (77%) as very important while 31% of respondents felt that technical complexity was not important at all. At the same time, 69% were of the view that it was important to have a model with easily determined input variables. The preferred model qualities response was an important feedback as the qualities preferred would be used as a criteria for rating the list of identified models. Table 4 presents the aggregate of the scores as a percentage of each quality obtained from the study.

Table 4: Aggregate scores of the qualities based on the percentage of respondents who selected a rating value (n = 13)

QUALTIES*	**1**	**2**	**3**	**4**	**5**
Highly accurate	0%	8%	38%	46%	8%
User friendly	0%	8%	15%	31%	46%
Suitable for all commercial species in SA	0%	8%	23%	31%	38%
Easy to modify to different scenarios	0%	0%	0%	46%	54%
Estimate above ground carbon	0%	0%	0%	23%	77%
Estimate below ground carbon	8%	0%	8%	23%	62%
Includes all regions in SA	0%	8%	23%	54%	15%
Results easy to interpret	0%	0%	8%	31%	62%
Easy to use	0%	8%	15%	31%	46%
Easy to determine input variables	0%	0%	0%	69%	31%

(* 5 - Very important; 4 - Important; 3 - Maybe, 2 - Not necessary, 1 - Not sure)

Figure 3 presents a summary of the qualities from the survey for the "very important" category only. These qualities are an aggregate of all the 13 respondents' preferences. In order of importance or most preferred, they range from *Estimation of above ground carbon* to *Model technical complexity* being the least.

Other qualities which were suggested by some of the respondents are:

- Must satisfy National Treasury requirements;
- Monitorable, verifiable and reportable;
- Internationally credible;
- Open source; and
- Cost effective.

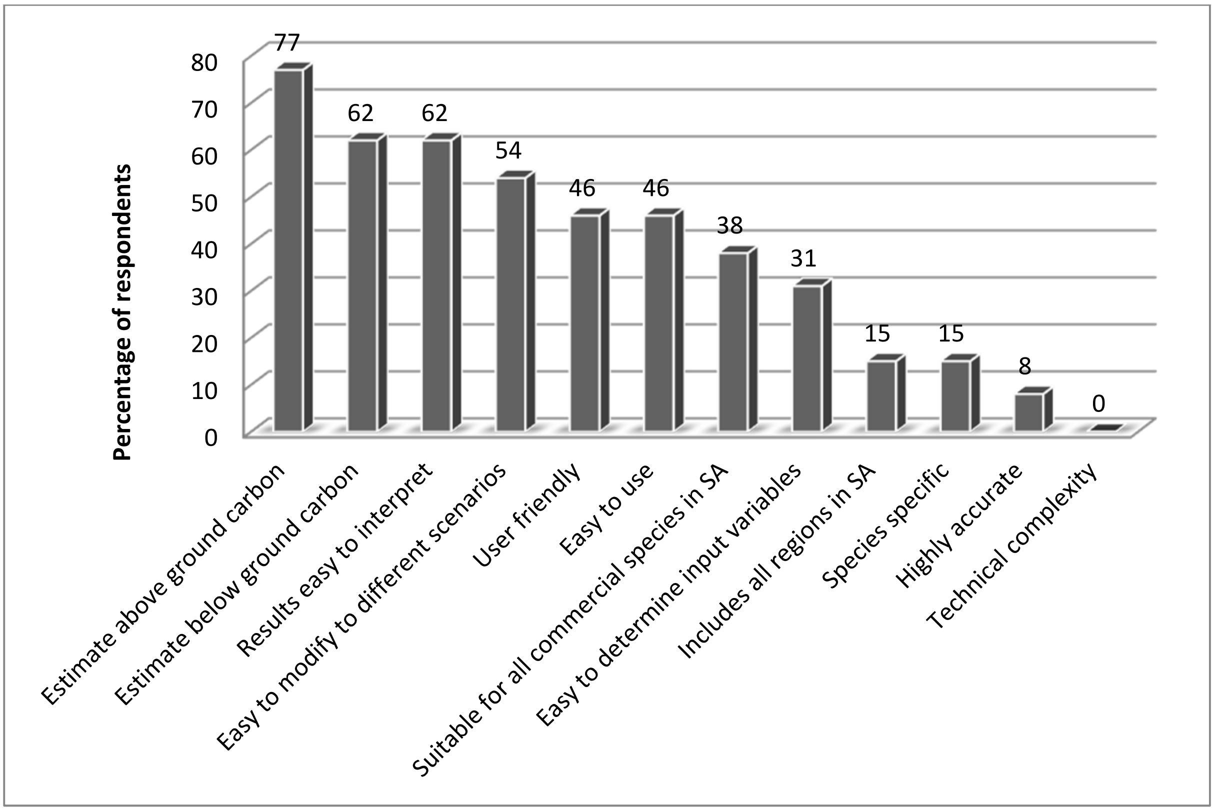

Figure 3: A summary of "very important" preferred qualities as indicated by respondents (n = 13).

4.3 Multi Criteria Decision and model choice

The percentage of respondents that selected the very important category per quality was selected for the quality weighting in the MCA matrix. The percentage score of each quality described how important the quality was to all the respondents. A model that has the capability to estimate above ground carbon is preferred by most respondents (77%) in this study as it came above all the other qualities. Respondents did not give as much importance to qualities such as technical complexity (selected by 0% of respondents as very important). The above qualities were then taken through a process of clarifying the criteria as some qualities sounded similar or could be confused as meaning the same thing. Criteria should be unique and coherent; hence from the above list, the following criteria were used by the researcher for rating the models;

- Estimate above ground carbon.
- Results easy to interpret.
- Estimate below ground carbon.
- Easy to modify different scenarios.

- User friendly/ easy to use.
- Easy to determine input variables.
- Suitable for commercial species in SA.
- Highly accurate.

The MCA matrix in Table 5 shows the merger between respondents weighting of qualities and the researcher's experience with the various models (rated from 5 - strongly agree, 4 - agree, 3 - disagree, 2 - disagree strongly and 1 - not sure).

Table 5: Cumulative scores for each model based on respondents' weighting and researcher's rating of models.

Model quality	**Weight***	**CASMOFOR**	**CBMCFS 3**	**3PG**	**FICAT**	**C02 FIX**	**GORCAM**	**CAM for**	**GERMIS**	**TIMBER CAM**	**C FIX**	**HWP**	**CAMSAT**
Estimate above ground carbon	77	5	5	3	4	3	4	4	1	1	1	1	1
Results easy to interpret	62	5	4	3	1	1	1	1	1	1	1	1	1
Estimate below ground carbon	62	4	4	1	3	1	1	1	1	1	1	1	1
Easy to modify different scenarios	54	4	4	1	1	2	1	1	1	1	1	1	1
User friendly/ easy to use	46	5	4	3	1	2	1	1	1	1	1	1	1
Easy to determine input variables	31	5	4	3	1	1	1	1	1	1	1	1	1
Suitable for commercial species in SA	38	5	1	3	1	2	1	1	1	1	1	1	1
Highly accurate	8	5	4	1	1	1	1	1	1	1	1	1	1
Totals		**1774**	**1475**	**886**	**733**	**670**	**609**	**609**	**378**	**378**	**378**	**378**	**378**

*Based on the percentage of respondents (n = 13) who selected this quality as very important.

Based on the MCA matrix CASMOFOR and CBM CFS 3 were selected as the top two models for further analysis, as their cumulative sum product was the highest (Figure 4). Quite a number of models received a rating of 1 (not sure) for qualities as it was not possible to determine the qualities from available information. This could penalise some of the models, but it is important to consider that the aim of the study is to find easily accessible models. It was also decided to include FICAT despite its low rating, because 23 % of respondents indicated it as an important model for the South African Forestry Industry currently.

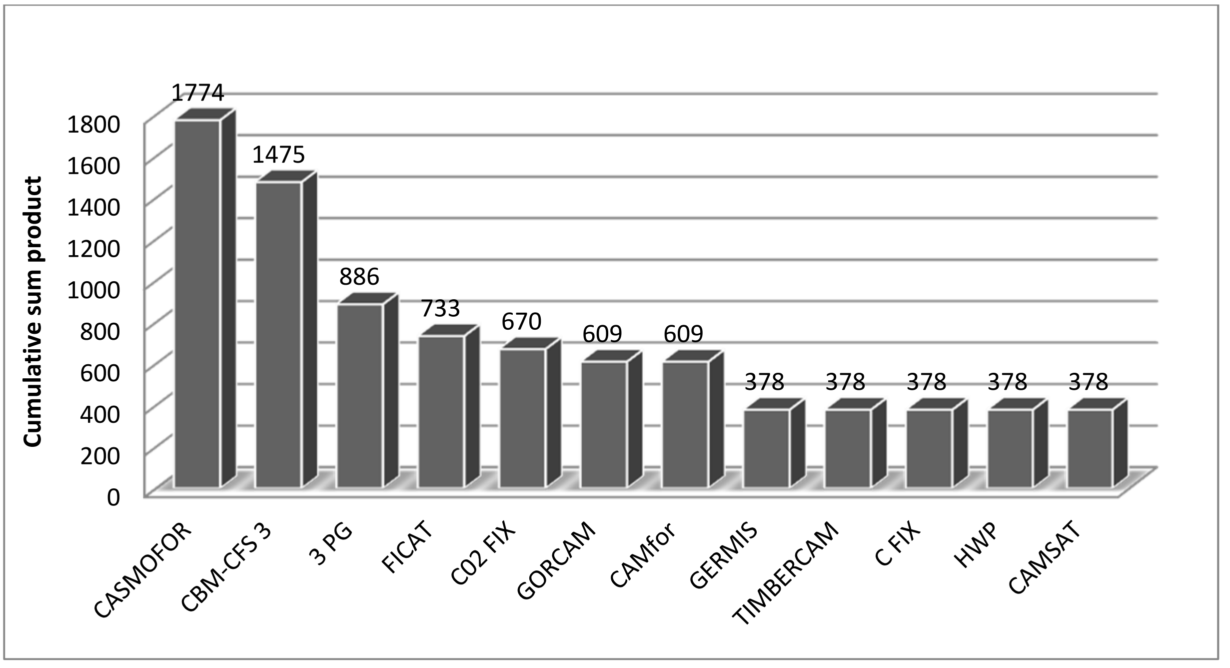

Figure 4:Multi criteria evaluation for models included in questionnaire survey.

The three selected models are described in more detail below.

4.3.1 CASMOFOR

CASMOFOR, short for CArbon Sequestration MOdel for FORestations, is an accounting model that was developed by Zoltán Somogyi to enable one to assess how much carbon is sequestered in a system of forests and primary forest industry over time in Hungary. The model has country specific parameters for Hungarian forests, but can be adjusted to include parameters for other countries' conditions. CASMOFOR's modelling framework can be used for any country where appropriate data are available to model basic forest and model forest management (Figure 5). CASMOFOR runs on Microsoft Excel spread sheets with Microsoft Visual Basic macros. Its input requirements are yield table data, wood density data, and other data and information on how stands are managed. Within the model an economic analysis of afforestations in relation to the amount of carbon fixed can be done (Somogyi, 2011).

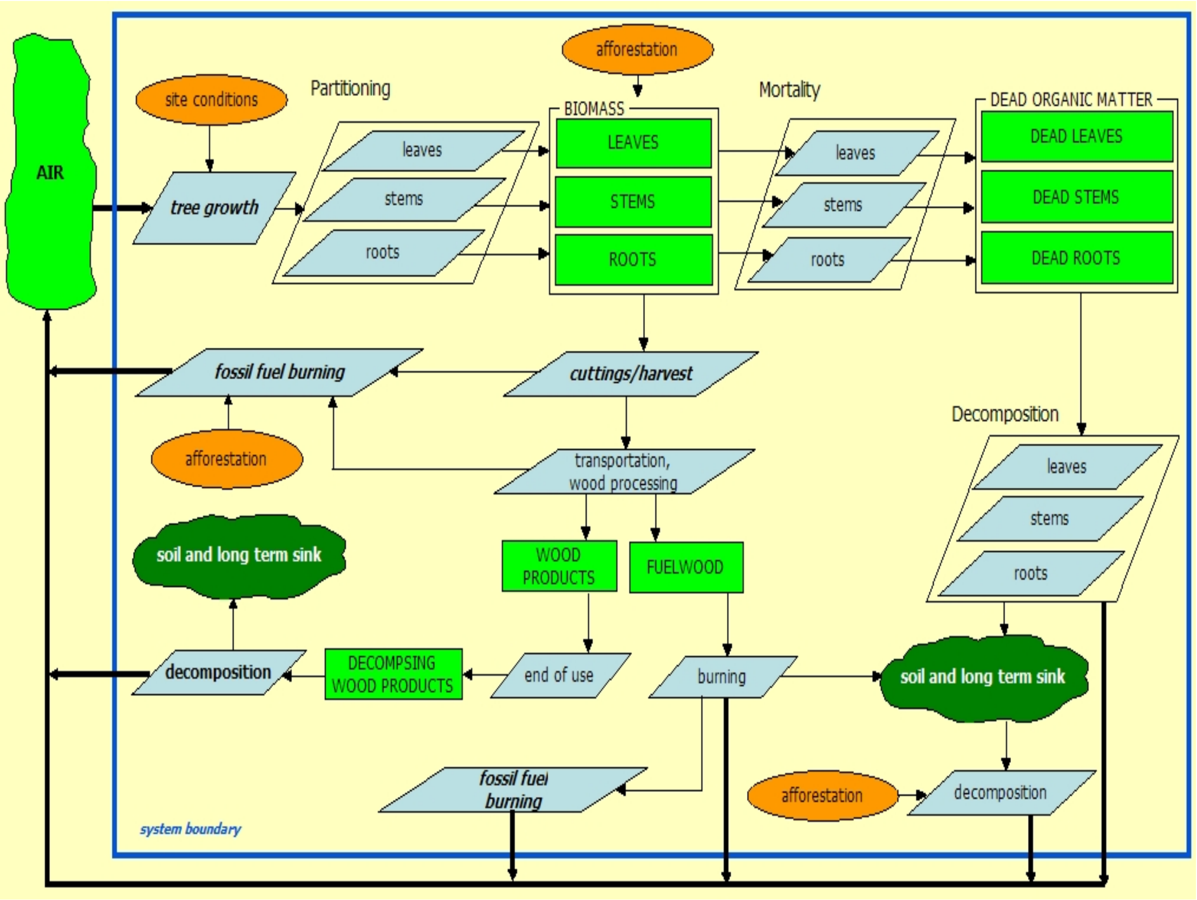

Figure 5:CASMOFOR conceptual framework (Somogyi, 2011).

The change in biomass (Delta B) for an entire forest area at any year (t), as the resultant of increases due to growth (G), and decreases due to mortality (M), thinnings (T) and final cuttings (FC) is modelled as follows:

Delta B = $G_t - M_t - T_t - FC_t$

In the model both thinnings and final cuttings are accounted for. In order to estimate biomass growth (G), the volume growth of woody parts of the above ground biomass is approximated from yield tables. When estimating volume growth, constants (basic wood density values) are used to estimate the increase of woody biomass increment of trees (Somogyi, 2011).

These constants, (biomass expansion factors) are used for the other biomass pools, i.e. leaves and roots in the calculation of above ground biomass. The total biomass calculation is a cumulative of various processes, and hence the resulting value is dependent on the accuracy in the preceding calculations (Somogyi *et al.,* 2006).

CASMOFOR does not directly model photosynthesis and respiration. This is the case as the process of continuously collecting data for environmental conditions is theoretically impossible. In order to calculate Net Primary Production, CASMOFOR uses growth models, drawn from historical growth trends. These yield tables have above ground volume, and hence make it easy to calculate and assimilate carbon accumulation per any given time period (CASMOFOR, 2013).

4.3.2 CBM CFS 3

The CBMCFS3 (Carbon Budget Model of Canadian Forest Sector - version 3) is a landscape-level model of forest ecosystem carbon dynamics that can be used by forest managers and analysts to assess the carbon stocks and changes in carbon stocks in their operational forest areas. It was designed by the Canadian Forest Service Sector and has been continuously revised to meet the standards described in the Good Practice Guidance (GPG) for land use (IPCC, 2003). It serves as the core component of the National Forest Carbon Monitoring Accounting and Reporting System of Canada (NFCMARS), (Kurz & Apps, 2006), to provide policy-support (Kurz *et al.*, 2009) and as a tool that meets the carbon accounting needs of operational foresters in Canada (Kurz *et al.,* 2002; Kull *et al.,* 2006).

Even though the model was primarily developed to assess carbon dynamics at the operational scale, it can also be used to explore carbon dynamics for smaller areas, down to the stand level (Kull *et al.,* 2006). CBM CFS 3 is a spatially referenced model which uses sophisticated algorithms to convert biomass volumes to carbon for specific locations in Canada. The model implements a Tier 3 approach, *" a more elaborate method used to estimate emissions or removals from most source and sink categories"*, of the (IPCC) Good Practice Guidance for reporting on carbon stocks and carbon stock changes resulting from Land Use, Land-use Change and Forestry (LULUCF) (Kurz *et al.,* 2009).

The model is driven by yield tables with a simulation of dead organic matter. Carbon is tracked as it is transferred between pools and other greenhouse gases such as methane (CH4) and carbon monoxide (CO). Yield tables provided by Boudewyn *et al.,* (2007) are used to estimate above ground biomass. The conversion to volume is done using a conversion factor of 0.5 g C/g dry matter (Lamlom & Savidge, 2003).

The model not only calculates above ground carbon, but below ground as well. The calculations are tied to the ecological zone from which data was obtained. All species in the model are related to the ecological zone and province they are specific to. Changes in landuse are also accounted for in CBMCFS3 because, globally, land-use change accounts for 20% of anthropogenic emissions of GHGs (IPCC, 2007b). It must be considered that the effects of land-use change can be both positive and negative (Kurz *et al.,* 2009).

Figure 6; is a process diagram for CBMCFS3 conversion of merchantable volume to growth increments from Kurz *et al.,* (2009) showing the process from yield table insertion within the model.

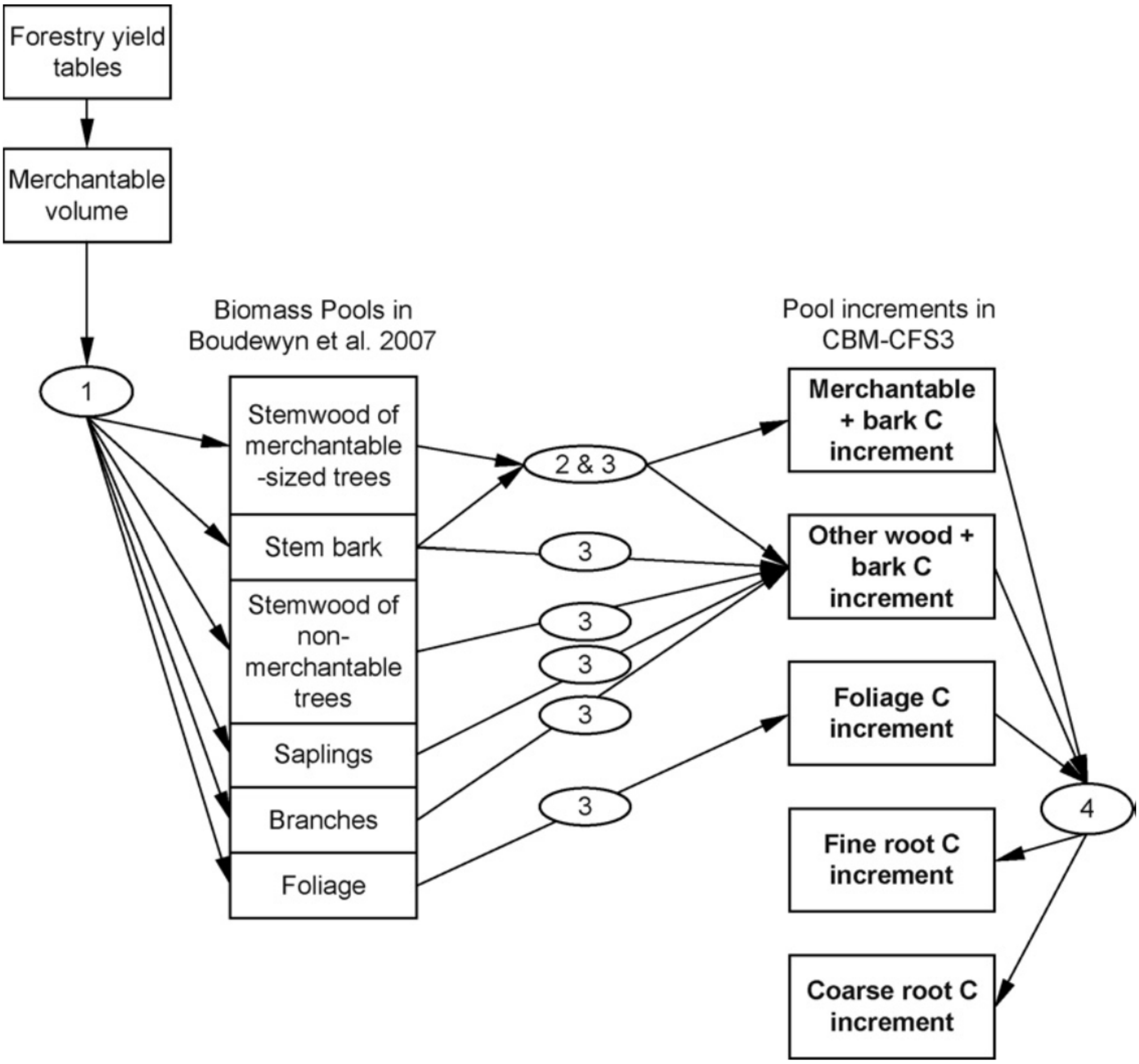

Figure 6: Process diagram for CBM CFS 3 (Kurz *et al.*, 2009).

The framework in CBM CFS 3was designed to simulate the impacts of land-use change, such as changes in land-areas and carbon stocks. The model was also designed to facilitate accounting of land-use change impacts following the requirements of the UNFCCC and Kyoto Protocol and the appropriate guidelines of the IPCC (IPCC, 2003, 2006). CBM-CFS3 provides a number of outputs useful for comparisons, which can provide valuable insight for decision making in forest ecosystem modelling (Kurz *et al.,* 2009).

Although developed for Canadian forests, the flexible nature of the model has enabled it to be adapted for use in several other countries.

4.3.3 FICAT

The Forest Industry Carbon Assessment Tool (FICAT) was developed by National Council for Air and Stream Improvement (NCASI) and International Finance Corporation (IFC) in the United States of America. FICAT looks at companies' emission impacts spanning the entire life cycle from forest beginnings through to product end-of-life (FICAT, 2013).

The assessment measures emissions and estimates avoided emissions using a 10 element tool designed by the Confederation of European Paper Industries (CEPI). The 10 elements in the framework include:

1. Carbon in forest ecosystems.
2. Carbon in forest products.
3. Greenhouse gas emissions from forest products manufacturing facilities.
4. Greenhouse gas emissions associated with producing wood.
5. Greenhouse gas emissions associated with producing other raw materials/fuels.
6. Greenhouse gas emissions associated with purchased electricity.
7. Transport-related greenhouse gas emissions.
8. Emissions associated with product use.
9. Emissions associated with product end-of-life.
10. Avoided emissions.

This study focused only on how the FICAT model account for carbon sequestration in forest ecosystems (element 1 of the 10 elements). For a more detailed description of the other nine elements in FICAT see FICAT (2013). When using FICAT, the user defines the area and period calculation. This is the case as FICAT already has IPCC default values which one can override if they have specific site information. The model uses stock change accounting to calculate the net transfers of biomass carbon to or from the atmosphere. Under stock change accounting, net transfers of biomass carbon to the atmosphere are determined by summing all of the changes in stocks of stored biomass carbon along the value chain. All default values in FICAT are from Tier 1 of the IPCC (Parigiani *et al.,* 2011).

Currently a default figure of 26.9 t ha^{-1} is used by PAMSA for South Africa in their calculations. They have, however, submitted a query to NCASI for a possible review of the value (Coppens, 2013).

Having described the three models in detail, this next section looks at the results obtained from running the models and the different statistical results obtained. Since the main objective was to see which model was a better predictor of the carbon calculated over *E. smithii'*s 15 year life span, t-tests as well as scatter plots are shown to highlight the differences.

4.4 Model results comparison

After adjusting the CASMOFOR and CBM CFS 3 models to South African conditions as well as using the FICAT model default value for South African conditions (as described in Chapter 3), these models were used to predict the cumulative amount of carbon per year for a 15 year rotation of a *E. smithii* stand. Dovey (2009) biomass expansion functions together with a carbon estimate of 0.5 tC^{-1} of biomass (Lamlom & Savidge, 2003) were applied to yield tables for *E. smithii* (Kotze *et al.,* 2012) to create a cumulative carbon estimate for a 15 year *E. smithii* rotation. This was done for low, medium and high site conditions and served as a benchmark against which the fit of the three carbon models could be tested. The results are presented in table 6 and figure 7.

Table 6: Carbon accumulated predictions by each model and estimated from yield tables (Kotze *et al,* 2012) with the use of Dovey (2009) biomass expansion functions for *E. smithii* (values in t/ha).

				Carbon estimates from yield tables		
Years	**CASMOFOR**	**FICAT**	**CBM CFS**	**Si 22**	**Si 18**	**Si 14**
1	2.22	26.9	0.01	0.04	0.01	0.01
2	4.06	53.8	16.34	3.39	0.65	0.15
3	11.4	80.7	34.41	17.92	11.04	4.95
4	25.3	107.6	39.82	39.35	23.25	12.79
5	38.2	134.5	44.53	58.99	36.91	19.94
6	49.6	161.4	57.81	76.23	48.98	27.29
7	59.43	188.3	62.17	90.95	58.19	33.64
8	66.34	215.2	66.89	101.27	66.29	38.36
9	72.28	242.1	70.42	109.9	71.92	43.15
10	76.67	269	71.43	116.53	77.29	45.97
11	79.86	295.9	71.54	121.21	81.29	48.37
12	82.23	322.8	72.39	124.71	83.72	50.12
13	84.12	349.7	74.96	127.52	86.2	51.41
14	87.12	376.6	75.07	129.88	87.6	52.52
15	92.83	403.5	76.45	131.14	88.78	53.28

T-tests were carried out to see if there was any significant difference in the means of the models from table 6. When all the models are compared using a Bonferroni test, (α=0.05), the result shows that there is a significant difference (p value=0.0001) between FICAT and the other models as well as the carbon estimates for the three site conditions. There were no significant difference (p-value= 0.9380) between CBM CFS 3, CASMOFOR and the estimates of carbon for the three different site conditions.

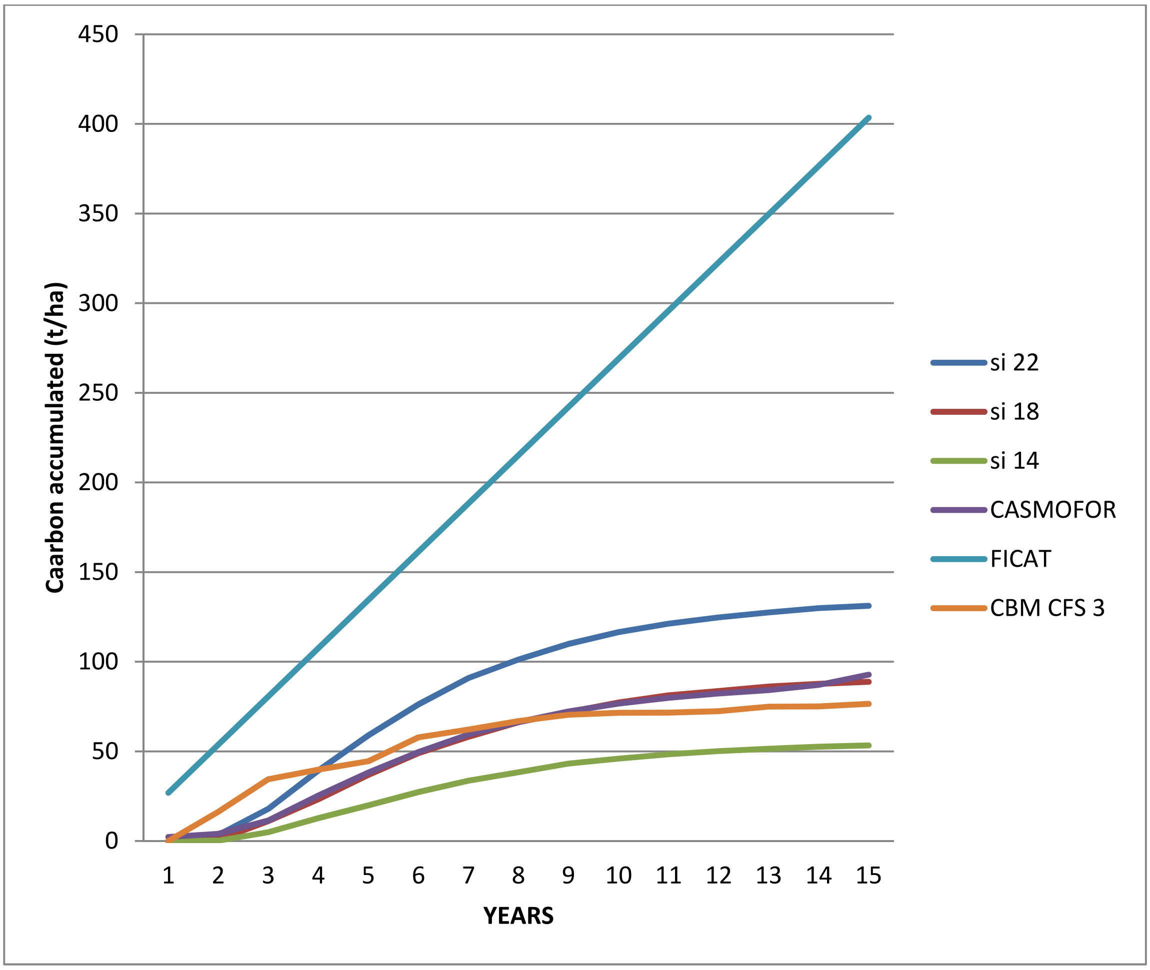

Figure 7: Carbon accumulated predictions by each model for *E. smithii* (t/ha).

According to Figure 7 the FICAT model continues to increase linearly with a factor of 26.9 t/ha whilst all the other models follow the same trend as the Dovey (2009) carbon estimates for a low, medium and good site (whose means were not significantly different). It should be noted that yield tables summarizes per unit area basis all essential data relating to the development of a fully-stocked and regularly thinned even-aged crop at which seems not to be the case in FICAT estimate. Each model's fit against the yield table data for poor, medium and good sites is explained below.

4.4.1 CASMOFOR

The CASMOFOR model predicts with high accuracy the yield table data (Kotze *et al.,* 2012) sites varying from poor to best. Its r values ranged from 0.9963 to 0.9989 for the poor site and good site. The strong and positive relationship between the CASMOFOR and the varying sites is supported by p values of (0.0000) for all the three sites. Figures 8 to 10 depict the relationship as explained.

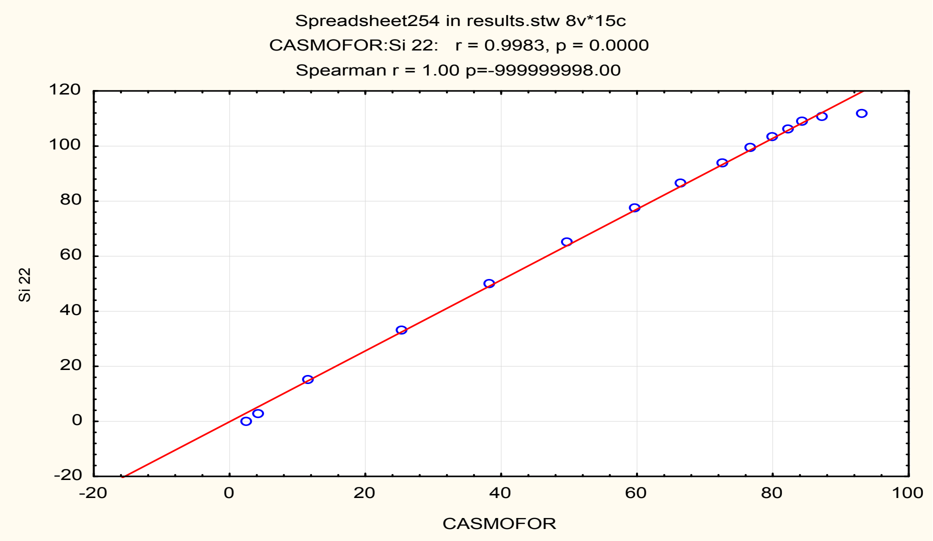

Figure 8: Comparison of carbon estimates per year (1 to 15) for CASMOFOR against yield table estimates for a high site index (22) site.

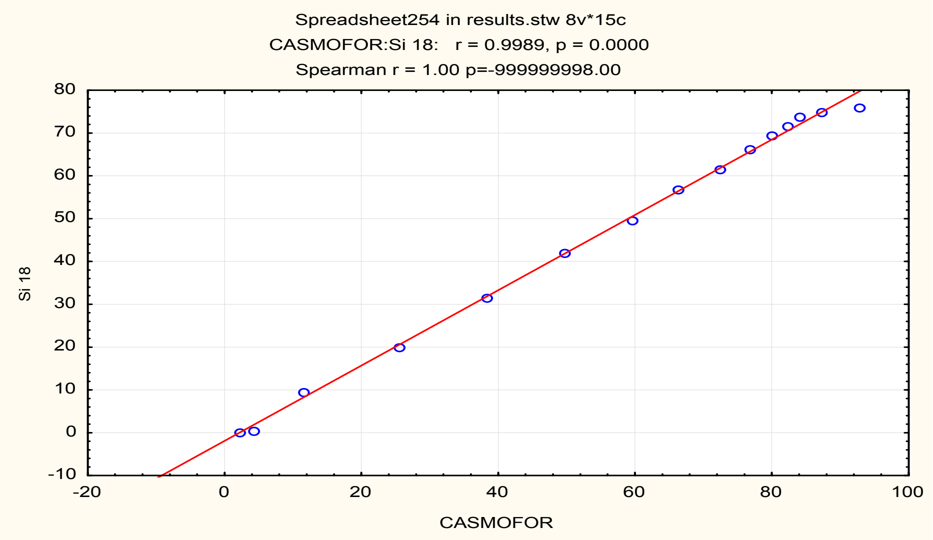

Figure 9: Comparison of carbon estimates per year (1 to 15) for CASMOFOR against yield table estimates for a good site index (18) site.

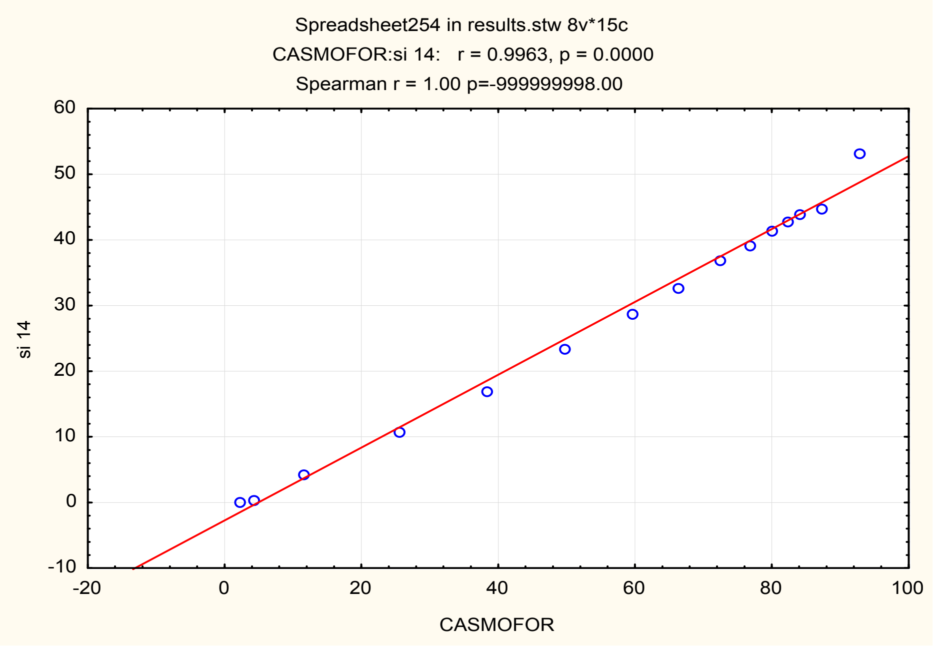

Figure 10: Comparison of carbon estimates per year (1 to 15) for CASMOFOR against yield table estimates for a poor site index (14) site.

4.4.2 CBM CFS 3

The CBM CFS 3 model's prediction of the different sites is different most times and has certain points (years) in which its estimates are in line with the sites. This is mostly for the early years, but beyond year (point) 8 there seems to be some harmony in the prediction. Even though this is the case, its relationship to the three sites is strong and positive, as seen by r values ranging from 0.9702, 0.9641 and 0.9463 for the best, good and poor site prediction respectively. Figures 11 to 13 show the relationship of the model versus the sites.

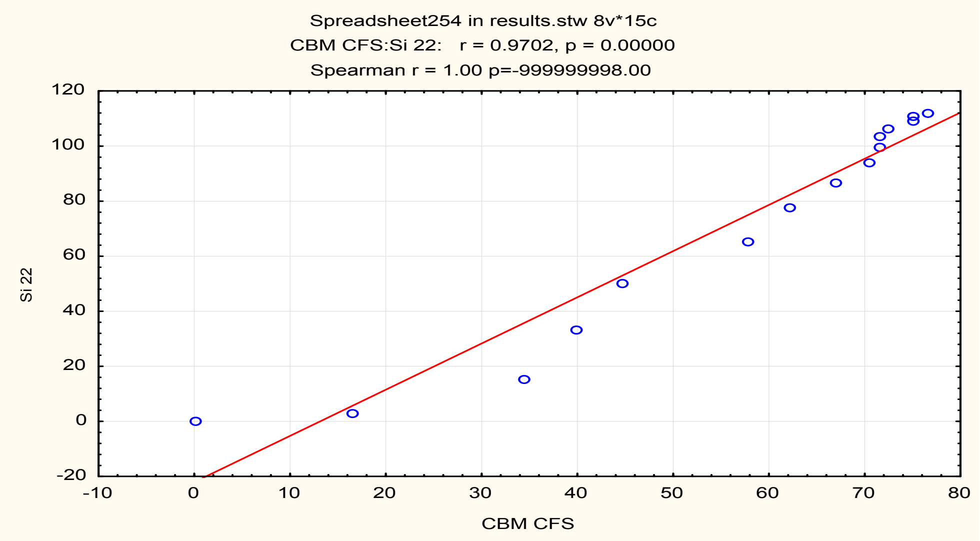

Figure 11: Comparison of carbon estimates per year (1 to 15) for CBM CFS 3 against yield table estimates for a high site index (22) site.

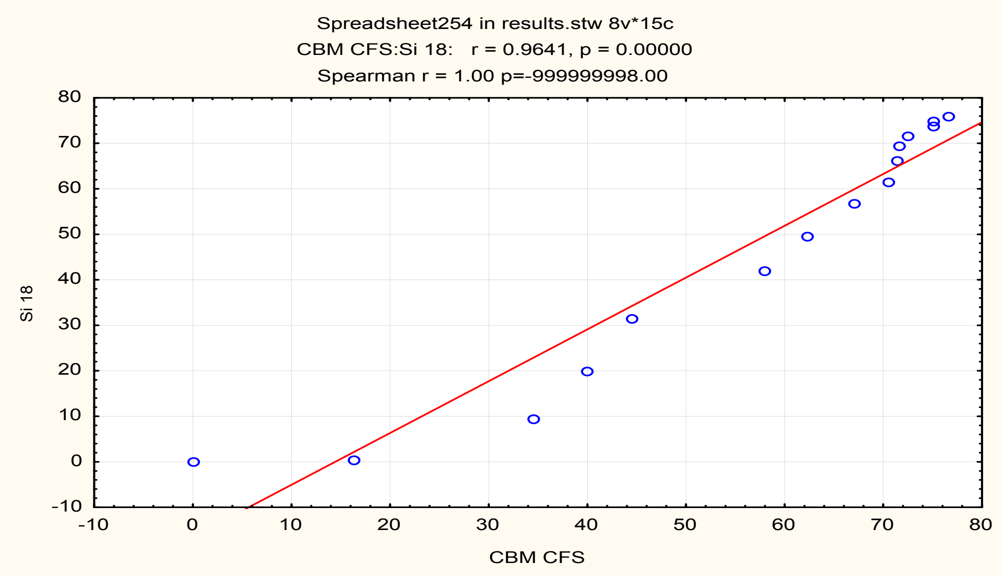

Figure 12: Comparison of carbon estimates per year (1 to 15) for CBM CFS 3 against yield table estimates for a good site index (18) site.

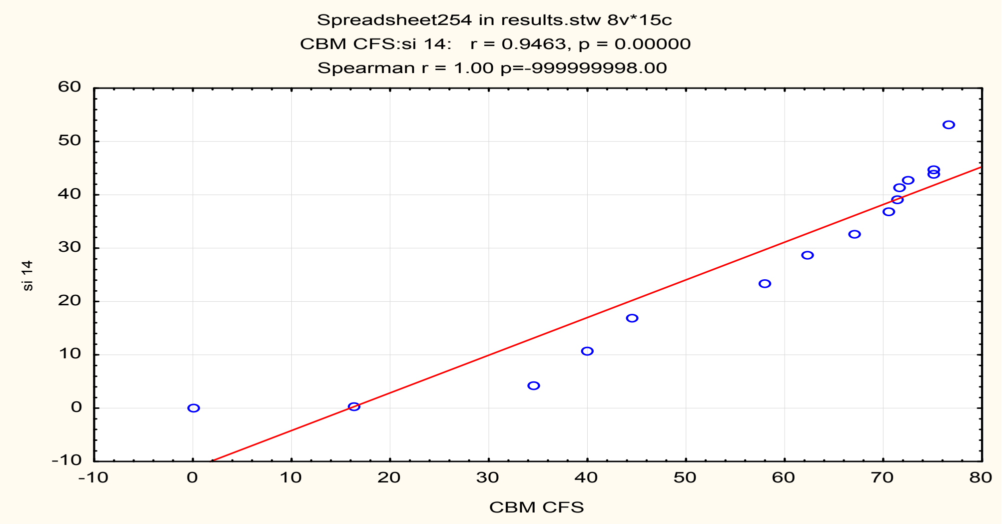

Figure 13: Comparison of carbon estimates per year (1 to 15) for CBM CFS 3 against yield table estimates for a poor site index (14) site.

4.4.3 FICAT

The FICAT model values over predict all the sites varying from poor to best. With r values ranging from (0.9540) to (0.9776) the relationship between FICAT and the yield tables seems to increase as the site changes from best to poor. This shows a high and positive relationship between the FICAT estimates and calculated carbon values for the three sites, as strongly supported by p values of (0.0000) for all the three sites. Regardless of having a strong and positive relationship with the yield tables, FICAT values are, however, much higher and not even close to any of the values from the other models. For example, in year 10 FICAT predicts 269t/ha of carbon whilst the best is only at116.53 t ha^{-1} with the medium and low sites having 77.29 t ha^{-1} and45.97 t ha^{-1} respectively for the same year. On the other hand the CASMOFOR and CBM CFS 3 predict 76.67 t ha^{-1} and 71.43 t ha^{-1} for the same year 10. Figures 14 to 16 show the relationship in detail.

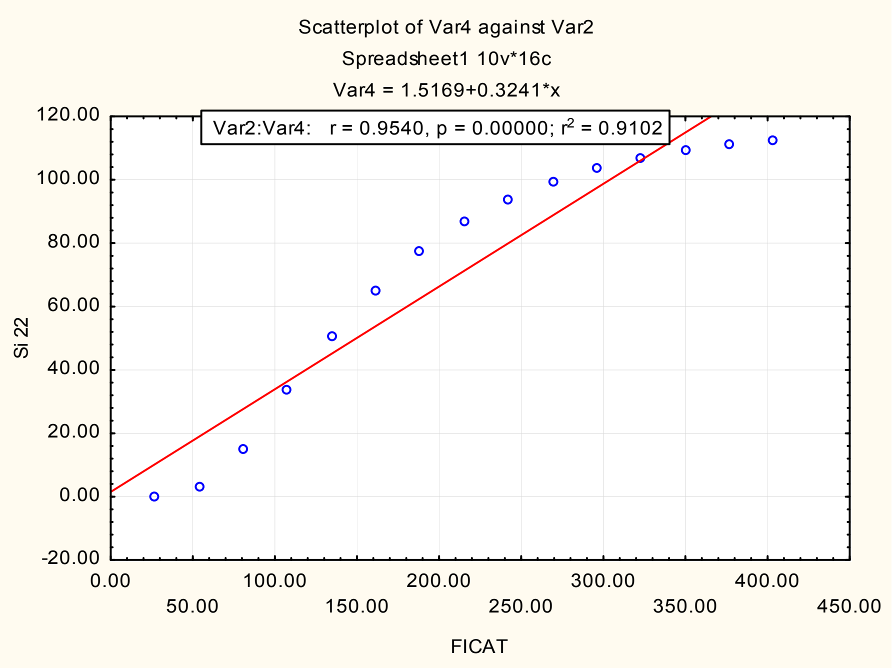

Figure 14: Comparison of carbon estimates per year (1 to 15) for FICAT against yield table estimates for a high site index (22) site.

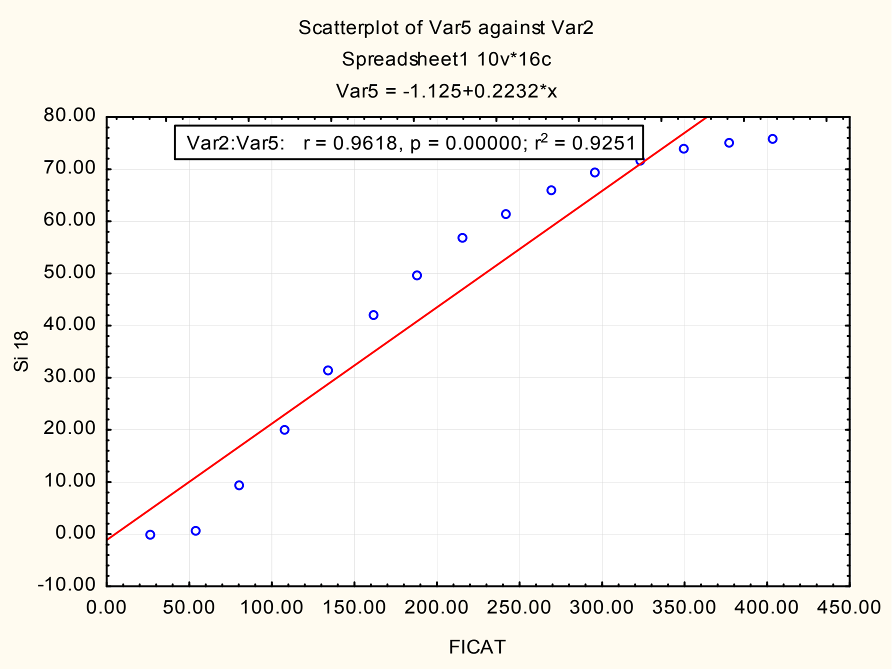

Figure 15: Comparison of carbon estimates per year (1 to 15) for FICAT against yield table estimates for a good site index (18) site.

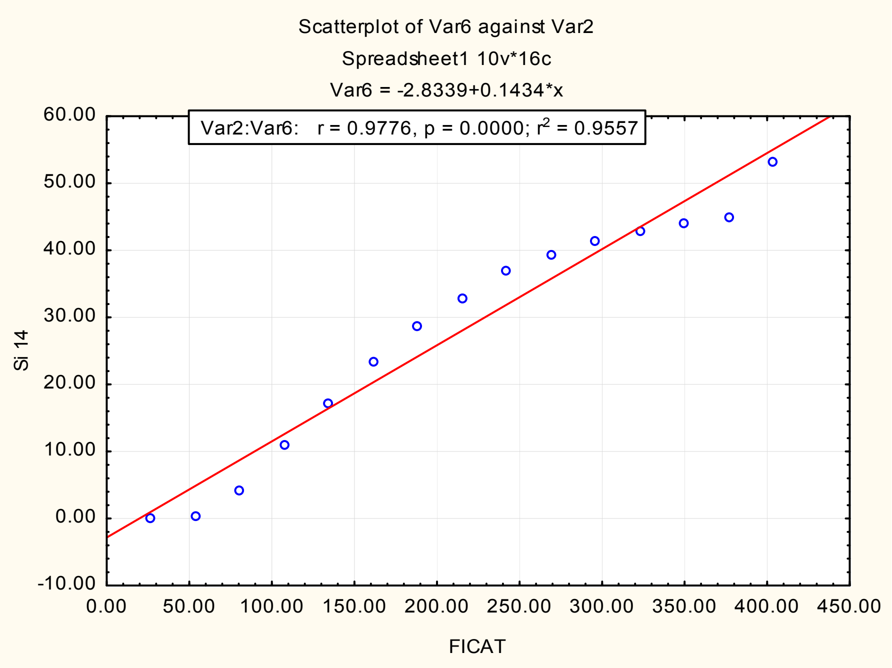

Figure 16: Comparison of carbon estimates per year (1 to 15) for FICAT against yield table estimates for a poor site index (14) site.

After comparing the yield table outputs versus the models, the next section looks at the models capabilities to predict carbon sequestered at Enon plantation.

4.5 Enon carbon estimates and comparison with selected models

The enumeration data from Enon shows that 24.45 m^3 of merchantable timber per hectare for *E. smithii* is available at year 3, 167.26 m^3 at year 6, 232.58m^3 at year 9 and 360.04 m^3 at year 14 (the plantation did not have any 15 year old trees standing at the time of the study). This volume per hectare was transformed to biomass per hectare with Dovey (2009) biomass expansion functions and then to carbon per hectare with a 0.5 multiplier (Lamlom & Savidge 2003). The amount of carbon per hectare, range from 9.3 t in year 3 to 137.01 t in year 14 as shown in (Table 7). The data from the Enon plantation inventory was used to test against the prediction of carbon per hectare for the four age groups by CASMOFOR, CBM CFS 3and FICAT.

Table 7: Carbon accumulated in Enon plantation using Dovey (2009) biomass expansion factors.

ENON			
Years	Utilisable Volume (m^3/ha)	Biomass (t/ha)	Carbon(t/ ha)
3	24.45	18.61	9.30
6	167.26	127.30	63.65
9	232.58	177.02	88.51
14	360.04	274.03	137.01

Figure 17 summarizes the comparison between the models and the calculations obtained from Enon. FICAT continues to predict higher carbon values than the two models and the Dovey (2009) estimate of the planation carbon in all the years. At the same time the two models CASMOFOR and CBM CFS 3 closely predict the Enon carbon values.

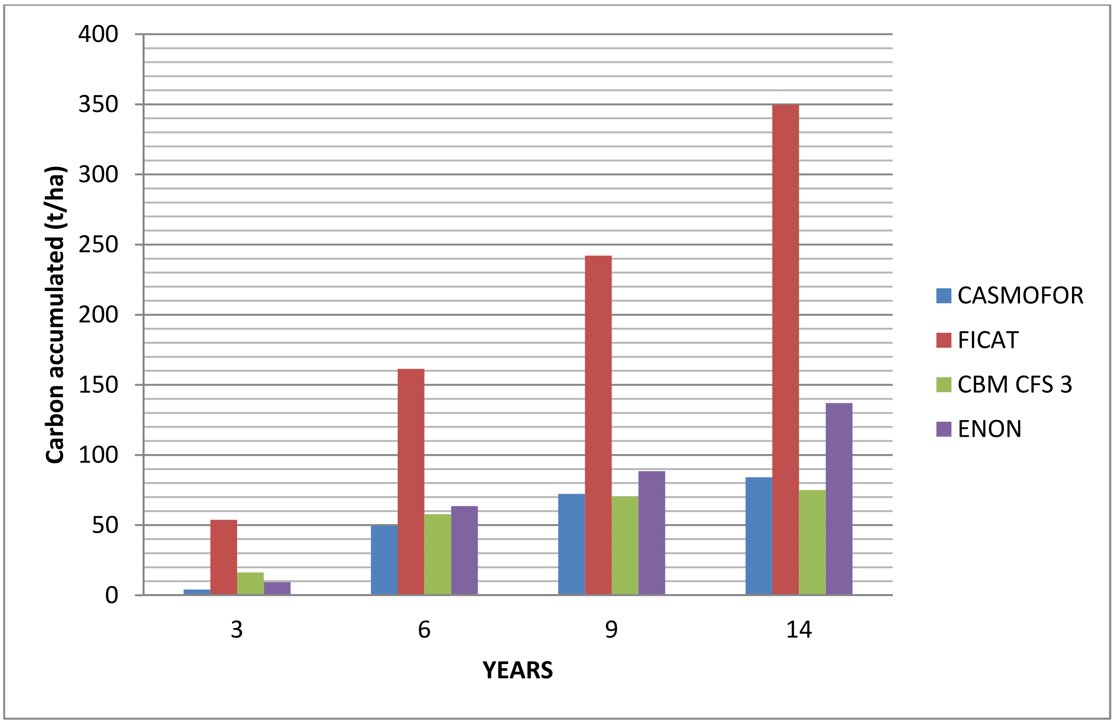

Figure 17: Carbon accumulated predictions by each model for Enon plantation (t/ha).

There is a significantly strong positive relationship between CASMOFOR and Enon plantation carbon estimates as supported by the p value of 0.0338 and the r value of 0.9662 (Figure 18). With the exception of year 14 where the calculated value for Enon (137.01 t/ha) is higher than predicted by CASMOFOR (84.12 t/ha) the model slightly under predicts for years 3 (9.3 t ha^{-1} vs. 4.06 t ha^{-1}) and 6 (88.5 t ha^{-1} vs. 72.28 t ha^{-1}) but within reasonable limits.

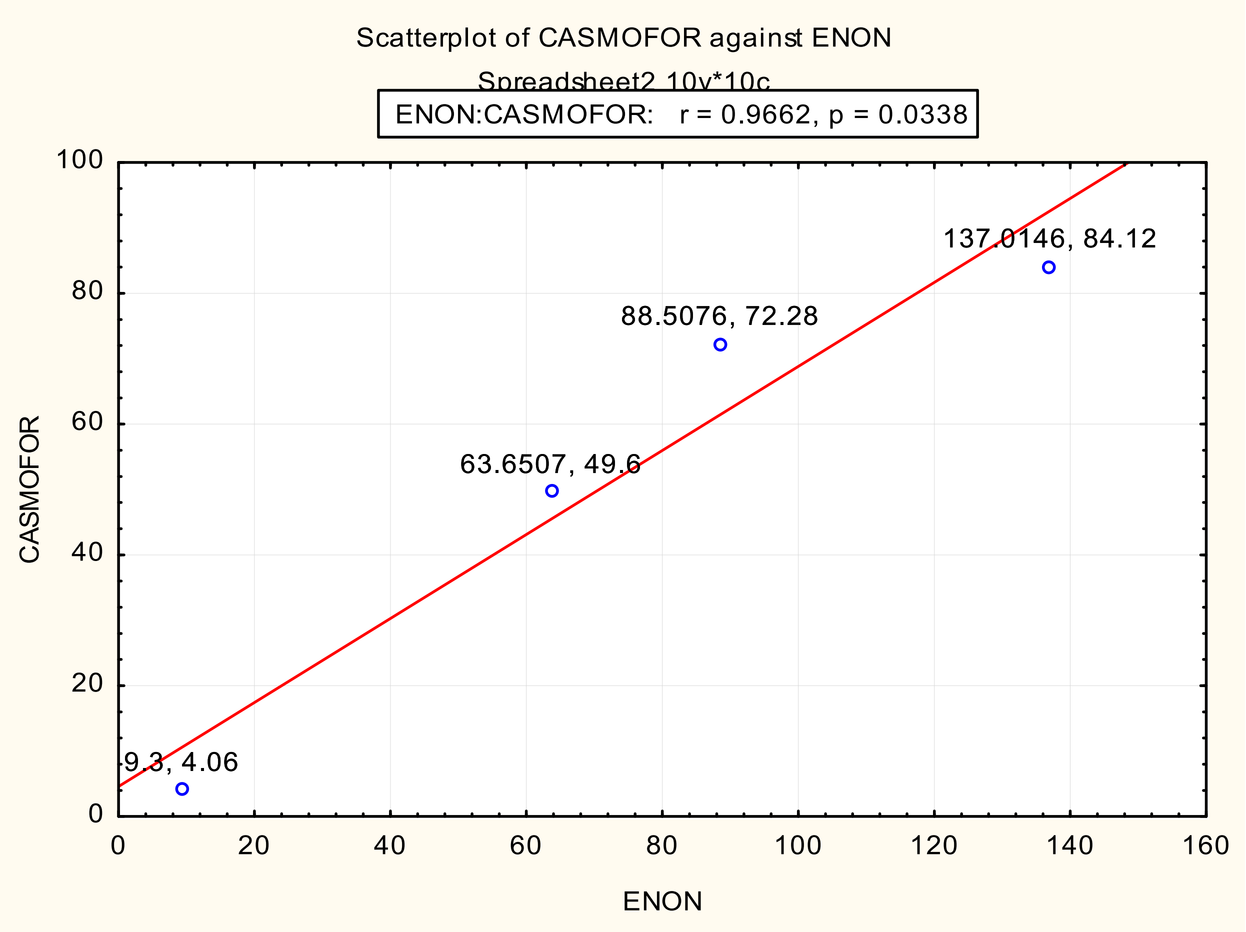

Figure 18: Prediction of carbon based on CASMOFOR vs. estimates from Enon for years 3, 6, 9 and 14.

The CBM CFS 3 model starts by slightly over estimating the carbon in Enonfor year 3 (16.34t/ha vs. 9.3t/ha) but from year 6 (57.81 t ha^{-1} vs.63.66 t ha^{-1}) through to 9 and 14(74.96 t ha^{-1} vs. 137.02 t ha^{-1}) it continues to underestimate the carbon accumulated in Enon. There is however a strong positive relationship as indicated by the p value (0.0414) but it has a lower r value of (0.9188) compared to CASMOFOR showing a less perfect fit to the datapoints (Figure 19).

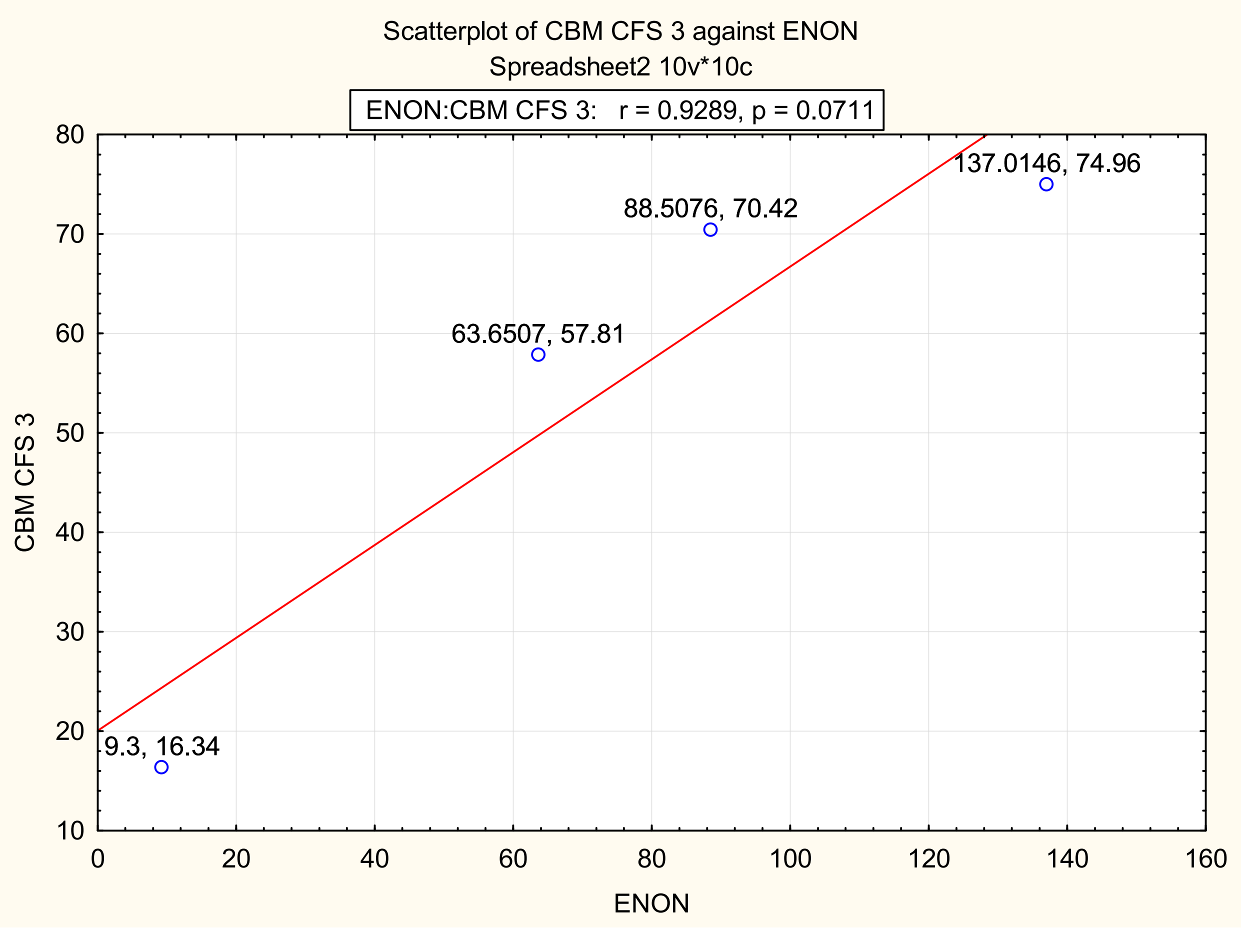

Figure 19: CBM CFS 3 vs. estimates from Enon for years 3, 6, 9 and 14.

The FICAT model starts by over estimating the carbon and the trend is the same for the years 6, 9 and 14. At year 3 (53.8t/ha vs. 9.3 t/ha) carbon values from FICAT are five times higher than in Enon, and even at year 14 (349.7t/ha vs.137.02t/ha)the model's values are still nearly three times higher than the plantation estimates. This is regardless of the r-value 0.9849 showing a strong positive relationship between the model and the plantation. The significance of the strong positive relationship is supported by the p value of 0.0151.

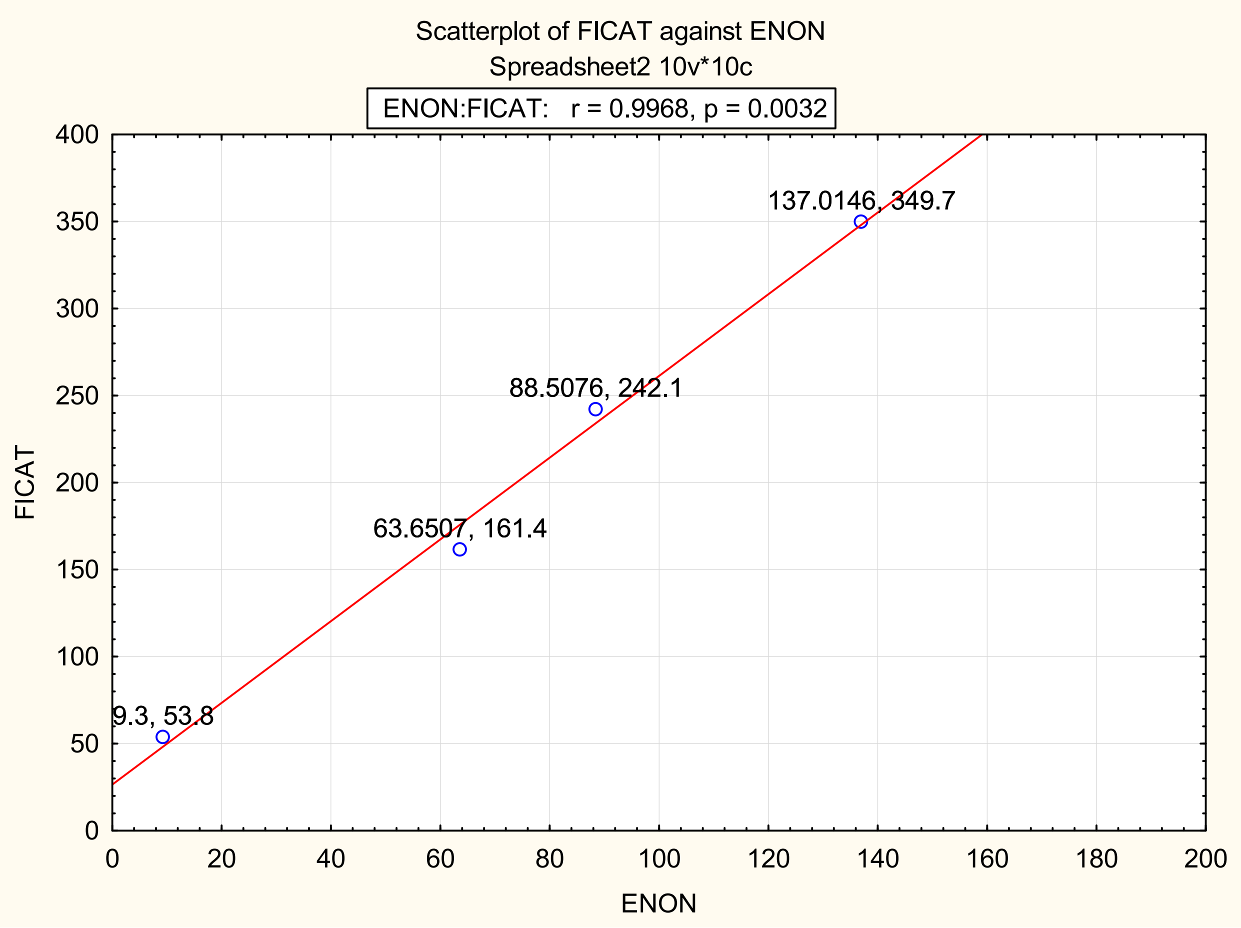

Figure 20: FICAT vs. estimates from Enon for years 3, 6, 9 and 14.

4.6 Best predictor results

When a MSE comparison was carried out for the years 3, 6, 9 and 14 the CASMOFOR model has the better aggregate predictor compared to the other models, as it has the smallest MSE as shown in table 8. When the MSE is calculated for the years 1- 9, CASMOFOR has the smallest MSE (465.17); making it the most accurate in estimation of carbon for Enon for the years, 1 to 9. This is the same for the years 1 to 14 though the MSE increases to (2954.63).

Table 8: Best predictor using mean square error

Year	**Carbon estimate from field data (t/ha)**	**Carbon predicted by model (t/ha)**		
		CASMOFOR	FICAT	CBM CFS
3	9.30	4.06	53.8	16.34
6	63.65	49.6	161.4	57.81
9	88.51	72.28	242.1	70.42
14	137.01	84.12	349.7	74.96
	MSE	**2954.63**	**95644.69**	**4829.28**

4.7 Chapter Summary

This chapter presented the results obtained from data collection and the presentation followed through the identification of the models and their detailed differences in system requirements. The results where visually presented by scatterplots when the models were compared against the yield table outputs. The three models correlated well with the yield tables and the plantation. CASMOFOR was the better predictor with the least MSE, seconded by CBM CFS 3, and finally FICAT. This is regardless of FICAT showing a strong correlation ship with the plantation. The following chapter will discuss the results.

Chapter 5: Discussion

5.1Introduction

This chapter discusses the results of the study as presented in chapter four. It starts with the discussion of the data collected from the stakeholder groups and how the results obtained were in line with the objective of gaining an understanding of the current carbon sequestration methods employed in the South African Forestry Industry. It ventures into the selection and choice of a model(s) most suitable for South African conditions. The chapter presents the qualities that an ideal South African model ought to have and ends with a brief discussion of the models and their suitability to South Africa.

5.2 Relevance of carbon models/tools in South Africa

The questionnaire survey found that South African forestry companies do not have a uniform way of assessing carbon. This comes as no surprise, for even in the United Kingdom it was noted that companies were disclosing carbon data in an incomparable and inconsistent way and only on a voluntary basis (ACCA, 2008). The Ethical Corporation Institute (2007) claimed, in a survey of 500 companies in the UK, to have uncovered 34 different carbon emission measurement methodologies. Such a large variation in practice cannot be helpful to a financial market facing increasing emphasis on carbon exposure and climate change risk. South Africa is no exception, but can become better by agreeing on techniques to measure and account for carbon.

The majority of survey respondents (77%) indicated that there is a need for carbon models to quantify the amount of carbon sequestered by plantation forests in South Africa. This view is supported by Birdsey *et al.,* (2006) who argues that carbon sequestration needs to be estimated for forests sooner rather than later and that the value of credits should be tied to the precision and accuracy of carbon sequestration estimates. This is further supported by the need for reliable estimates of the carbon sequestered in their forest stands by landholders to begin carbon trading (Preece *et al.,* 2012). The survey respondents indicated that it is, however, not just important from a carbon trading perspective, but also to quantify the industry’s environmental impact, to prepare for carbon taxes, for FSC certification and as a response to the National Climate Response Policy.

Further research should endeavor to improve accuracy of estimates across a broad array of forest conditions (Maier & Johnsen, 2010) especially in South Africa with diverse biophysical conditions and a large number of indigenous as well as exotic tree species. It is important to have a model that caters for the different forest conditions and that can be used by anyone from any region in South Africa.

The need for a South African carbon sequestration model fits well with international agreements (UNFCCC and Kyoto Protocol) which require countries to monitor and report on forest carbon stocks or stock changes. More importantly policy demands for the ability to project and estimate future carbon stock changes are also increasing (Kurz*et al.,* 2009).

5.3 Preferred qualities of a carbon model

The qualities of a good carbon model are always better determined by those people who are going to put it to use or who already use one. The survey respondents for instance, placed quite a high premium on the user friendliness of models (Easy to interpret – 62% of respondents, Easy to modify to different scenarios – 54% of respondents and User friendliness - 46% of respondents). It should be noted, however, that models have to strike a balance between user friendliness, which usually means low level of complexity and flexibility, and the required depth of parameterizing and analytical options. In the case of carbon forestry modelling to help analyse climate change related forest management options and to quantify the true mitigation potentials of forest management, very simple and easy to use models might not be the most suitable solution (Somogyi, 2013).

Most respondents (77%) indicated however, that models should be able to predict the amount of above ground carbon sequestered. The importance of being able to calculate with accuracy above ground carbon relates to Government policies related to carbon tax (RSA, 2010), potential future need to report on carbon sequestration for FSC certification and carbon trading. The estimation of above ground carbon does not require high level photosynthesis based models but simpler yield table based models.

McCall *et al.,* (1977 cited by Ortega & Rojas, 2003) highlighted three working areas in systems which could help to align user quality preferences to the right kind of model for a specific purpose. These working areas are product operation, product revision and product transition. Product operation refers to the product's ability to be quickly understood, efficiently operated and capable of providing the results required by the user. This is seen by the industry defining what qualities they need in a model as well as which ones rank higher.

Product revision is related to error correction and system adaptation, and this quality is described as being able to be modified for different scenarios. Fifty four percent of respondents agreed that any carbon model of choice or recommended should be able to be revised and modified. Product transition even though it is not as important as revision and operation, influences the importance of the product to the end user. These working areas correlate well to the preferred qualities of carbon models and could be used as a reference for the selection of carbon models.

5.4 Available models and software

The need for models and software in climate change and carbon modelling arises from the need for powerful computer programmes to enable researchers to make and communicate important climatic decision to government and the population at large. Many environmental experts have, however, developed software applications, regardless of failing to find proper synergy with computer scientists and users (Liu *et al.,* 2008). Some models and software, for example, GORCAM, were designed during a project life span. Once the project ended the model and software support came to an end, making it impossible to use outside of the defined parameters of the project for which it was intended.

Model and software being products largely draw interest based on their qualities. Based on the study findings, model input requirements will determine whether or not a particular model can be used. The complexity of input data requirements such as leaf-area index, climate variables, and soil variables, at time steps ranging from hourly to monthly in photosynthetic models e.g. the Australian 3PG model, make them unpopular even though they might calculate accurately carbon in plantations (Kurz *et al.,* 2009).

Gorte, (2009) acknowledges that the complex views on how to account for carbon arises from the complexity of biological processes and carbon sequestration in forests. This explains the differences in countries on how to count carbon sequestered or released from forests. The IPCC (2007b) guidelines have tried to harmonize the methodologies to bring the complexities to an end or a mutually agreed position where different countries all follow similar steps.

5.5 Biomass measurement

Central to sequestered carbon estimates is the assessment of biomass. Biomass assessment has two major objectives: (1) for resource use and (2) for environmental management. It is important to determine how much biomass is available for use (Parresol, 1999; Zheng *et al.,* 2004). Biomass is also an important indicator in carbon sequestration. For this purpose, one needs to know how much biomass is lost or accumulated over time. The Kyoto protocol requires transparent reporting of forest removal and accumulation (biomass change), which translates to precision in the procedures of quantifying forest biomass and all its uncertainties (Samalca, 2007).

The need for accuracy in biomass sampling can never be over emphasized. The actual number of sample trees is determined by the level of precision required and the variability of the resource, with the principle that model bias should be entirely avoided (van Laar & Theron, 2004). There is always a trade-off between accuracy and efficiency of the sampling procedure and the higher the accuracy of the results, the more the cost and time investment. The Dovey (2009) biomass expansion functions currently serves as a useful tool to convert utilisable timber values, as determined by various enumeration techniques, e.g. Bredenkamp, (2000) into biomass estimates. It offers a simple technique that affords rapid and cost-effective estimation, from which operational decisions may be made.

Seifert & Seifert (2014) explain the reason why the use of constant biomass expansion factors such as Dovey, (2009) without further adaptations has been criticised. They mention their inability to adapt to changes in the relationship between stem volume as well as being limited to predictions within the same parameterisation data. This is despite the fact that they are widely applied in tropical and subtropical regions. They instead propose a model for the estimation of biomass proportions that simulates foliage and branch biomass according to obtained proportions. These are then multiplied by the stem biomass with the obtained proportions. This means all biomass fractions can be determined because the value for the stem biomass is fixed and the proportions are known.

5.6 Models for South African conditions

An ideal model for South African should possess the following qualities:

- Highly accurate;

- User friendliness;
- Species specific;
- Suitability for all commercial species in South Africa;
- Ease in modification of different scenarios;
- Estimation of above ground carbon;
- Estimation of below ground carbon;
- Includes/encompasses all regions in South Africa;
- Simplicity in result interpretation;
- Easy to use;
- Technical complexity; and
- Ease of determining input variables.

The model ought to be monitorable, reportable and verifiable. The carbon models/ programmes selected from a range of internationally available ones, had to be, "modifiable, reliable, efficient, integrity and usable", according to McCall *et al.,* (1977 cited by Ortega & Rojas, 2003).

The study's aim was to find a model(s) most suitable for South African conditions. Two models had these qualities in this study, CASMOFOR and CBM CFS 3. FICAT was used in the comparison only because it came as a recommendation by the survey respondents. The suitability of the models to South African conditions will be discussed in the following sections

5.6.1. FICAT

FICAT was singled out by 23% of survey respondents that did not think South Africa needed a new model. FICAT is supported by PAMSA and FSA and suits secondary processing companies such as pulp and paper mills as it not only considers what happens in the plantations but includes the activities to and after the pulp and paper mills. Parigiani *et al.,*

(2011) summarise the motivation for a company to use FICAT to calculate its carbon footprint as the "*desire to identify potential liabilities and opportunities, to inform internal and external discussions on environmental sustainability, and to be an active participant in efforts to develop carbon footprint methodology*".

Presently, companies increasingly understand that global carbon emissions regulation, with the imminence of emissions-trading systems is here to stay. Matthews, *et al.* (2008) wrote that, "*...Many organizations are already pursuing carbon emission inventory projects to set a baseline for their carbon footprints in preparation for future carbon mitigation projects. Most of these groups look to the protocols for guidance in how to prepare their footprint inventories. However, our results suggest that these protocols will, in general, lead the organizations to footprint estimates that are relatively small in comparison with their total life-cycle footprints…*" This statement justifies why companies will take the carbon footprint route for estimating carbon.

It is, however, important to note that footprint models, unlike carbon sequestration models, have to deal with the complexities of the product life cycle from cradle to grave. Companies, both small and medium encounter major problems in practice when trying to calculate their footprint (Schmidt, 2009). Carbon footprint models should thus provide a relatively simple balance between carbon sequestration and carbon emissions. FICAT can be customized by companies to incorporate site-specific information in any of the IPCC areas (FICAT, 2013), although manipulation or making changes in the model cannot be made without permission from NCASI.

Although the model came as a recommendation by respondents, it has some shortfalls as observed by Preece *et al.,* (2012). The model (FullCAM) on which FICAT runs ignores stems less than 10 cm DBH, and hence all the shortfalls of the model (FullCAM) are automatically adopted by anyone using FICAT. Not only that but FullCAM is based on another model, CAMFor, which runs a version of the 3-PG model that needs parameterisation to account for the difference in the productivity values in the tropics.

Preece *et al.,* (2012) concludes by saying, "*The data and assumptions used in NCASI urgently need to be revised to include the age-incremental growth models; the assumed carbon fraction in wood; and the assumed average wood density. A revised 3-PG model for the Wet Tropics should be incorporated.''*.

These observations largely affect FICAT's outputs and estimations where South Africa is concerned. It is important then to have within the model system values that are in line with South African conditions. The sooner these default values are rectified the better, considering PAMSA's current position in vying for the model's adoption by the industry at large.

5.6.2. CBM-CFS3

The CBM CFS 3 could work for South Africa but with much work needed to build the model to suit the South African conditions. This is the case as the observed differences encountered when calculating with CBM CFS 3 are based on default model parameters as it was designed specifically for Canada. The model ties carbon calculations to an ecological zone (Kurz *et al.,* 2009), making it necessary to populate the model with information of all ecological zones in South Africa as a first step.

Secondly there would be a need for introducing biomass information for all relevant species from South Africa. This can be done by developing and documenting new methods to estimate stand-level biomass from a country inventory and by assigning biomass data to every vegetated ecological zone (Boudewyn *et al.,* 2007).

The model uses a smoothing algorithm to calculate the non-merchantable biomass carbon in each stand based on the growth curve that is entered for each stand. Most Canadian species do not grow anywhere near as fast as those in tropical climates, so this difference can influence problems for the smoothing algorithm when it comes to fast growing species such as *E. smithii*. The usual solution is to turn off the smoothing algorithm (Kull, 2013). This can be addressed once the model has been populated with South African ecological information and biomass information.

5.6.3. CASMOFOR

Based on results from this study, the model is suitable for South Africa because it gives the user the freedom to change and manipulate the scenarios according to the afforestation project they want (Somogyi, 2011). CASMOFOR uses a simple excel based framework and once populated with the right information it becomes easy and manageable to use. CASMOFOR predicted with higher accuracy the carbon in Enon than the CBM CFS 3 and FICAT models (as can be seen from its lower MSE value of 957.44). This is largely because the model meets all five of the characteristics of modifiability, reliability, efficiency, integrity and usability (McCall *et al.,* 1977 cited by Ortega& Rojas, 2003) which are important in the success of any software or model. Furthermore there was the advantage of having guidance from the developer.

It should be noted, however, that by design the CASMOFOR uses six yield classes. This allows for a fine enough resolution to map the differences in site fertility over a large area. Where there is sufficient data, or a project does not fully cover the site fertility range of any plantation or area, extrapolations can be made within limits (Somogyi, 2013). With more yield tables populated in the model its accuracy will improve.

Where values for other pools such as deadwood, litter and soil are not available, the model uses default values in line with the IPCC (2007b) requirements. The wood density value input in the model was0.586 g/cm^3 (Zanne *et al.,* 2009) as opposed to the 0.581 g/cm^3 used by Dovey (2009).

Since the model was built to enable assessment of the amount of carbon sequestered in forests and for the primary forest industry over time (Somogyi, 2011), it can be useful to the South African forestry industry as a model to help in carbon sequestration. This is regardless of whether the industry decides to adopt other footprint models.

5.7 Chapter Summary

Chapter 5 discussed the data collected within this study. It highlighted the difference between the models' prediction of carbon in Enon. These differences are most noticeable when the MSE was carried out on the accuracy of the predictors and are explained in the model structures. The Hungarian CASMOFOR model is a better predictor of carbon in Enon and shows a good relationship with the poor, good and better sites. On the other hand the FICAT model needs to be parameterized if it is to be adopted for use by the South African forestry industry. CASMOFOR and CBM CFS 3, unlike FICAT can be used by small companies and individuals to calculate the carbon in their plantation regardless of how small an area they might have.

Chapter 6: Conclusions and Recommendations

6.1 Conclusion

This chapter presents the study's conclusions and recommendations based on the study objectives outlined in Chapter 1.

The purpose of this study was to gain an understanding of the current carbon sequestration methods the South African forestry currently employs. The findings showed that the industry does not have an agreed method in measuring carbon, but there is a consensus in the industry for identifying one. At the same time one of the industry associations, PAMSA, has gone ahead and is currently advancing the adoption of the FICAT model.

There are a large number of carbon estimation models and software programmes available from literature (Table 1), making it difficult to select the most appropriate model or software programme. In selecting an appropriate model it is important to consider the kind of qualities that would fit the forestry industry's needs. The model qualities that were identified as the most important are:

- Highly accurate;
- User friendliness;
- Species specific;
- Suitability for all commercial species in South Africa;
- Ease in modification of different scenarios;
- Estimation of above ground carbon;
- Estimation of below ground carbon;
- Includes/encompasses all regions in South Africa;
- Simplicity in result interpretation;
- Easy to use;

- Technical complexity; and
- Ease of determining input variables.

By applying these qualities in a multi criteria decision analysis it was possible to identify the Hungarian CASMOFOR model and Canadian CBM CFS 3as potential models for South African conditions. When these models (and FICAT as recommended by respondents), were compared for prediction of carbon accumulation in NCT's Enon plantation, outside Pietermaritzburg, the Hungarian CASMOFOR model was found to be the better predictor among the three.

The Hungarian CASMOFOR model from this study is the model best suited for adoption and use by the South African industry. At the same time being mindful of companies' needs for Corporate and Social Responsibility (CSR), a carbon footprint model, is better suited for the industry's needs. For all other calculations small and medium plantation owners, can use the model as it has shown it is accurate.

Internet models can significantly underestimate or overestimate carbon sequestered in different places from which they were developed, and hence there is a need for parameterisation of any model to suit the conditions that it will be adapted to.

6.2Recommendations

The following recommendations are based on issues identified in the study:

Selection of a South African carbon model

It would be in the interest of the South African Forestry Industry to use a model that was tested on South African conditions as opposed to "one size fits all" solution such as FICAT. Models developed in other countries will be determined by countries' national forest circumstances, their technical and institutional capacities, cost-effectiveness, and the financial, technical, and institutional support received and might not fit to South African conditions.

The recommendations listed below should be used in conjunction with existing IPCC guidance to form the foundations on which results-based forest carbon measuring and monitoring for REDD+ are built as they apply to the South African case in line with developing or adopting any carbon model.

- Monitoring reporting and verification should integrate and coordinate field-based forest carbon inventories and remotely-sensed land cover change analyses and other datasets and this should be compatible with potential future efforts to measure and monitor the impacts of anthropogenic activities on other land uses.
- Forest monitoring systems should augment field-based carbon inventories, and should ultimately be accomplished using wall-to-wall mapping at the national scale.
- Frameworks should be able to track changes to and from forest land in a spatially-explicit manner *(IPCC, 2003).*

Companies with comprehensive forest inventories from many sites and species should share their actual tree volumes and wood densities information, to improve the allometric equations used in modelling primary production. A bigger information data base will make room for improved estimations on a wider area as is the case with CBM CFS 3 (Boudewyn *et al.,* 2007) and CASMOFOR (Somogyi, 2011).

Model quality

Carbon models will continuously be developed. Agreed standards, need to be set before each company ends up adopting a model or software they see as fitting their needs. Differences in model preferences are expected but general benchmarks should be set. And the study recommends, the sooner the industry sets the ball rolling the better.

There is a need for dialogue and information sharing where carbon monitoring, reporting and verification are concerned. This is the case as the contribution of each company is ultimately added to the national values hence again the need for some uniformity in measurement and sharing of information.

In order to enable individuals/organisations to calculate their CO_2 emissions accurately information should come from credible and regularly updated sources (Subedi *et al.,* 2010). There is a need for transparency in calculations for any model or procedures that companies small or large choose to follow in their carbon quantification exercises.

Adoption of FICAT

The decision by PAMSA to adopt FICAT as an internationally credible model is a welcome move, but caution should be paid to the calculations of plantation carbon. If the carbon sequestration calculations are over or under predicted it will influence results through the company value chain and product life cycle.

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Appendix A

Companies and institutions represented by respondents in the Survey

- University of Pretoria
- PAMSA
- Mondi
- Cape Pine Holdings (Pty) Ltd
- ICFR
- Forestry solutions
- Forestry South Africa
- Eudardo Mondlane University (Mozambique)
- Global Carbon Exchange SA (Pty) Ltd
- Lion Match Forestry (Pty) Ltd
- Grasslands.org
- MTO Forestry Pty Ltd.
- Fractal Forest Africa
- Department of Agriculture Forestry and Fisheries
- ForestLore Consulting
- South African National Parks
- SANBI
- Sappi Forests
- Forest Wood
- PG Bison
- Stellenbosch University
- Working for Water
- Future Works
- York Timbers
- SAFCOL

Appendix B

Survey: Forestry Carbon Model

June 2013

Dear Stakeholder

We are currently conducting a survey amongst forestry stakeholders to learn more about ideas and perceptions regarding forestry carbon modelling. Your opinion is very important to us and we will appreciate it if you can please complete the attached questionnaire. Your comments will be treated as confidential. Please e-mail or fax the completed questionnaire to Cori Ham (e-mail: cori@sun.ac.za, fax: 021 808 3603) before 30 June 2013.

We will also send a summary of results to you. If you need more information please contact me at 082 771 9540.

Yours sincerely

Cori Ham

1. Relevance of carbon models/tools in South Africa		
1.1. Do you think that the SA Forestry Industry needs its own forest carbon model/tool/calculator? (Yes/No)		
1.2. Please elaborate on your answer in 1.1.		
1.2. Do you or your company/organisation have experience with the estimation of carbon on plantations/farms? (Yes/No)		
1.3. If **Yes**: Why did you estimate carbon values? For: 1.4. Which method have you used to estimate carbon values? 1.5. If **No**: Please provide reasons.		

2. Qualities of a carbon model

2.1 Please rate the following carbon model qualities(5. Very important; 4. Important; 3. Maybe, 2. Not necessary, 1. Not sure; 0. Not applicable).

Carbon model qualities	**Rating**
Highly accurate	
User friendly	
Species specific	
Suitable for all commercial species in SA	
Easy to modify to different scenarios	
Estimate above ground carbon	
Estimate below ground carbon	
Includes all regions in SA	
Results easy to interpret	
Easy to use	
Technical complexity	
Easy to determine input variables	
Other qualities….	

3. Existing forest carbon models

3.1. Are you aware of any existing forestry carbon models/tools?		
3.2. Have you used any forest carbon model/tool before?		
1.3. If yes, please name the models/tools.		
3.4. Would you recommend these models/tools for use (adoption) in South Africa?		
3.5. Why would you recommend these models/tools?		

3.6. Below is a list of forest carbon models. Please indicate if you have used any of them and

rate those that you have used (1. Excellent; 2. Very good; 3. Good; 4 Average; 5. Poor).	
3PG – A stand level model for simulating forest growth.	
CAM For – Carbon accounting model for forests.	
CAMSAT – Carbon management self-assessment tool for companies to measure carbon offset.	
CASMOFOR – Carbon Sequestration Model for Forestations.	
CBM-CFS 3 – Operational-Scale Carbon Budget Model of the Canadian Forest Sector.	
C-FIX – Carbon uptake monitoring through satellite images.	
CO2FIX – One of the oldest carbon accounting applications available, somewhat outdated.	
GEMIS – Global emission model for integrated systems.	
GORCAM – Graz / Oak Ridge carbon accounting model, Excel spread sheet.	
HWP Harvested wood products – dead wood carbon assessment.	
Timber CAM – Carbon in wood products assessment.	
FICAT	
General comment	

Thank you for your time!