

**ESTIMATION OF CARBON STOCKS IN UCHINDILE FOREST PLANTATION,  
KILOMBERO DISTRICT, TANZANIA**

**BY**

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**A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE  
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MANAGEMENT OF NATURAL RESOURCES FOR SUSTAINABLE  
AGRICULTURE OF SOKOINE UNIVERSITY OF AGRICULTURE.  
MOROGORO, TANZANIA.**

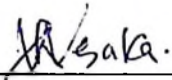
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## ABSTRACT

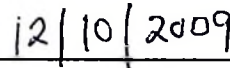
The study reported here was conducted to estimate carbon stocks in Uchindile forest plantation, Kilombero district, Tanzania. The tested hypothesis was *Pinus patula* and *Eucalyptus saligna* plantations had similar carbon sequestration. Data was collected from two main plantation species i.e. *Pinus patula* and *Eucalyptus saligna*. Stratified random sampling design was adopted. Three sample plots measuring 20 m x 20 m were established in each stand. Diameter at breast height (DBH) and height were measured for stand data estimation, especially volume. Top soil samples 0-15 cm and 15-30 cm depths were sampled. Then, total biomass and soil carbon stored in the plantation was prepared using Microsoft Excel. The CO2FIX was used to estimate biomass and soil carbon in the two plantations. Lundgren equations were used to estimate biomass in the pine plantations. For each species, stand ages selected were 4, 6, 8, and 10 years. Field data results indicated that at year 4, 6, 8, and 10 *Pinus patula* plantations sequestered stand biomass C of 7.48, 21.34, 42.22 and 61.48 Mg Cha<sup>-1</sup>. *Eucalyptus saligna* plantations sequestered stand biomass C of 43.5, 137.53 and 183.71 Mg Cha<sup>-1</sup>. *Pinus patula* plantation had mean soil C of 81.29, 80.03, 76.76 and 76.47 Mg Cha<sup>-1</sup> at year 4, 6, 8, and 10, respectively. *Eucalyptus saligna* plantation had mean soil C of 73.65, 86.06 and 77.77 Mg Cha<sup>-1</sup> at year 6, 8 and 10. The two plantations sequestered total C of 218.18, 342.04 and 399.43 Mg Cha<sup>-1</sup> at year 6, 8 and 10, respectively. This translates to 800.72, 1255.29 and 1465.91 Mg CO<sub>2</sub>ha<sup>-1</sup>, at the respective ages. Mg CO<sub>2</sub>ha<sup>-1</sup> = Mg Cha<sup>-1</sup> multiplied by 3.67. The T test indicated a very significant (P<0.05) difference in carbon sequestration between the two plantation species. *Eucalyptus* plantations sequestered 1.15 to 1.89 times more carbon in comparison to the pine.

**DECLARATION**

I, Ronald Makongoro Wesaka, do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work and that it has neither been published nor concurrently submitted for a higher degree award in any other University.



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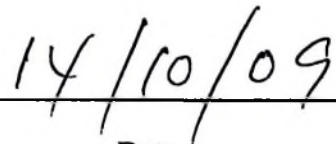


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(Supervisor)



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## **DEDICATION**

**This work is dedicated to my beloved parents: Makongoro S. Msangya and Agnes B. Mtiro who laid a good foundation for my education through their tireless assistance and encouragement.**

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**LIST OF ABBREVIATION AND ACRONYMS**

AGB	-	Aboveground Biomass
BA	-	Basal Area
BD	-	Basic Density
C	-	Carbon
CAI	-	Current Annual Increment
CDM	-	Clean Development Mechanism
CER	-	Certified Emission Reduction
CO <sub>2</sub>	-	Carbon dioxide
COV	-	Certification and Verification of greenhouse gas emission and sequestration activities
CS	-	Carbon Sequestration
DBH	-	Diameter at Breast Height
DM	-	Dry Matter
EFC	-	Escarpment Forestry Company
FAO	-	Food and Agriculture Organization
FSC	-	Forest Stewardship Council
GHGs	-	Greenhouse Gases
GRL	-	Green Resource Limited
ha	-	hectare
IPCC	-	Intergovernmental Panel on Climate Change
KFC	-	Kilombero Forest Company
KP	-	Kyoto Protocol
KFL	-	Kilombero forest plantation

m	-	Meter
m.a.s.l.	-	Meters above sea level
MgC	-	Megagram Carbon ( $10^6$ g $\approx$ 1 tonne)
MgCO <sub>2</sub> eq	-	Megagram Carbon dioxide Equivalent
N	-	Nitrogen
SD	-	Sustainable Development
SOC	-	Soil Organic Carbon
SUA	-	Sokoine University of Agriculture
UFP	-	Uchindile Forest Plantation
t	-	Tonnes (1000 kg)

## CHAPTER ONE

### 1.0 INTRODUCTION

#### 1.1 Background Information

Carbon sequestration (CS) is the reduction of carbon dioxide (CO<sub>2</sub>) in the atmosphere by different sinks. Green plants remove carbon from the atmosphere through photosynthesis, extracting CO<sub>2</sub> from the air to make biomass which is partitioned into roots, stems, and foliage. The major sources of CO<sub>2</sub> include industrial combustion of fossil fuels, cement production, and land use change. According to IPCC, 'the global average air temperature near the earth's surface rose  $0.74 \pm 0.18$  °C during the 100 years ending in 2005 and is expected to rise further from 1.1 to 6.4 °C during the 21st century' (IPCC, 2007). The greenhouse gases (GHGs) of significant importance are Carbon dioxide (CO<sub>2</sub>), Methane (CH<sub>4</sub>), Nitrous oxide (N<sub>2</sub>O), Perfluorocarbons (PFCs), Hydrofluorocarbons (HFCs), and Sulphur hexafluoride (SF<sub>6</sub>). The increase in greenhouse gases (GHGs) in the atmosphere is recognized to contribute to climate change (IPCC, 2007). For instance; the increase in greenhouse emissions caused by human activities leads to disturbances in the greenhouse mechanisms whereby more heat is trapped by the GHGs. This leads to an increase in the global warming as more heat will be re-emitted back to the earth (IPCC, 2001).

Whereas the major source of greenhouse emissions is from industrialized countries, deforestation of tropical forests leads to about 20-25 percent of anthropogenic carbon (C) emissions to the atmosphere (Kirby and Potvin, 2007, IPCC, 2007 and FCPF, 2008). It contributes 5-6 giga tonnes (Gt) of CO<sub>2</sub> emissions and massive collateral damage. Tropical deforestation emits about 1.5 (Gt) annually. Between 1990 and 2005 the rate of deforestation averaged 13 million hectares, mostly in the tropics (Merritt, 2008). According to FAO (2007), the amount of carbon emitted to the atmosphere has increased

from 6.8 Gt in 2000 to 7.9 Gt in 2006; while CO<sub>2</sub> emissions has increased from less than 1% in 1990s to more than 2.5% between 2000 and 2005.

Tanzania has about 150 000 ha of forest plantations under mostly pines and eucalyptus (Forest Policy, 1998). However, Tanzania is among the countries in the world experiencing high deforestation rates ranging from 130 000 ha to 500 000 ha per annum (Hamza and Kimweri, 2007). The high deforestation rate is ascribed to both direct and underlying or indirect factors. The direct agents of deforestation are: settlement and agricultural expansion, commercial charcoal and fuel wood production, overgrazing, uncontrolled fires, shifting cultivation and illegal logging.

Based on various scientific researches, the impacts of climate change are remarkable and include changes in weather patterns, a rise in the sea level, an increase in the global warming, an increase in the range of disease vectors, a drop in agricultural yields, and the extinction of some wildlife species (IPCC, 2001).

Mitigation efforts for reducing the concentration of CO<sub>2</sub> emissions in the atmosphere include, establishment of forest plantations on degraded lands and former pasture lands which has been shown to sequester large amounts of carbon (Vesterdal *et al.*, 2002). Carbon sequestration through planting trees (afforestation/reforestation) will help to stabilize the concentration of GHGs in the atmosphere by reducing the concentration of CO<sub>2</sub> emissions in the atmosphere (FAO, 2004). The amount of carbon sequestered will vary with growth rate, age, wood density, management, species, and the apportionment of biomass in parts of the tree with different carbon contents and longevity (Silver *et al.*,

2004; Vesterdal *et al.*, 2002). Both above ground and below ground tree components are important sinks.

Facts about carbon stocks and sequestration potential of trees will reflect the importance of forests in offsetting human-produced carbon emissions. However, fast growing forest plantations like tropical pines and eucalyptus are highly efficient in terms of carbon storage (Laclau, 2003). Moreover, soil carbon increases due to the death of roots plus litter decay from the forest floor (Silver *et al.*, 2004). According to FAO (2004), enhancing carbon sequestration in degraded lands could have direct environmental, economic and social benefits as well as mitigation of global warming effects until alternative energy sources are developed.

Traditional methods of estimating forest biomass rely on destructive sampling and weighing the various tree components (Lundgren, 1978). This is expensive, time consuming, and subject to various sources of errors. In order to estimate the amount of C sequestered in forest plantations, different computer simulation models have been developed. CO2FIX V3.1 an ecosystem level model based on a carbon accounting of forest stands, including forest biomass, soils and wood products (Schelhaas *et al.*, 2004) were employed in this study.

## **1.2 Problem Statement and Justification**

One of the major challenges of the 21<sup>st</sup> century is the mitigation and adaptation to climate change and global warming arising from increasing levels of greenhouse gases (GHGs) in the atmosphere caused by combustion of fossil fuels, cement production, deforestation, and degradation of agricultural soils (FAO, 2004). The concentration of CO<sub>2</sub> and other GHGs

in the atmosphere has increased by 1.3 higher than the pre-industrial levels and losses of biodiversity at up to 1000 times the background rate as a consequence of anthropogenic emissions (Kirby and Potvin, 2007). The concerns about climate change are driving the development of mitigation initiatives at local to international levels (FAO, 2004).

Afforestation and reforestation have been proposed as a means to offset C losses through the accumulation and long-term storage of C in plant biomass and soil organic matter (Brown *et al.*, 1996). According to FAO (2004), there have been few studies on the potential of carbon sequestration in developing countries. Seidl *et al.* (2007) reported that carbon storage in wood products is not always accounted for, since the wood product pools are not considered in the guidelines for the first Commitment Period under the Kyoto Protocol. However, considerable amounts of carbon are stored in long-lived wood products and thus, there is a need for an improved accounting methodology. Moreover, although afforestation and reforestation has been proposed as major mechanism of C sequestration, methods of quantifying C stocks in different tropical forest plantations of various species is little studied. My research aimed to fill this gap in knowledge using data from Kilombero Forest Project owned by Green Resource AS.

The Kyoto Protocol commits high polluting countries (Annex 1) to implement mechanisms to reduce emissions to certain levels specified by the Kyoto Treaty (UN, 1998). Low polluting countries (Non-Annex 1) have no legal obligations on emission reductions, but they can voluntarily help high polluters to achieve their emission targets through three mechanisms, i.e. Joint Implementation, Emission Trading, and Clean Development Mechanism (UNFCCC, 1997).

**Table 1: Proposed CDM Project Activities in Tanzania**

Title	Status	Type	Scale	Years	Developers/Consultants
Landfill gas recovery and Electricity generation at "Mtoni Dumpsite", Dar es salaam (Ref. 908).	Registered	Waste management			Biotechnogas as PDD Consultants
Afforestation on grassland areas of Uchindile, Kilombero, Tanzania & Mapanda, Mufindi, Tanzania.	PIN not approved; Opted voluntary market	Afforestation	Large	10	Green Resources as PDD Consultants
Tanzania Planting Company (TPC) Moshi-Bagasse cogeneration.	PIN submitted but not approved	Renewable energy	Large	20	TPC
200MW Singida Wind Farm.	PIN submitted	Renewable energy	??	??	Wind Energy Tanzania Ltd/CAMCO International
Biogas and energy Production From sisal waste.	PIN stage	Renewable energy	Small	??	Katani Ltd (Sisal Production Company)
Vingunguti Landfill Gas Capture and Power Project.	PIN stage	Renewable energy	Small	??	Mwanguya and Kyoto works
Biomass Cogeneration Project, Tanga Cement, (17.5MW).	PIN stage	Renewable energy	Large	??	Tanga Cement Ltd
Use of Biolatrine for methane capture and destruction at 5 prisons in Arusha, Moshi, and Tanga.	PIN stage	Waste management	Small	??	Carmatec Ltd, Arusha
Zege 70 kW Microhydro.	PIN stage	Renewable energy	Small	??	TaTEDO
Forest Plantation in Kimange, Kwang'andu & Rupungwi in Bagamoyo.	PIN stage	Afforestation	??	??	Community Development Corporation Ltd
Fuel switch from Diesel to Gensets to gas at Mtwara and Lindi.	PIN stage	Fuel Switching	Large	??	Artimus Tanzania Ltd
Same and Mwanga Forest Project.	??	Afforestation	??	??	Safari Jet Services Ltd
Tanzania Biomass Energy Efficiency Improvement.	??	Biomass energy	??	??	TASONABI

Source: Designated National Authority, Vice President's Office (2007).

Basically, these mechanisms allow high polluters to achieve emission reduction targets by purchasing emission credits through projects operating in low polluting countries (UNEP, 2005). CDM is intended for third world countries. It is expected that through CDM activities, third world countries could benefit by obtaining new technologies, conserving the environment, accessing cleaner energy, improving production processes, and ultimately achieving sustainable development. Despite all of these opportunities, currently Tanzania has only one registered CDM project (UNFCCC, 2008).

The clean development mechanism (CDM) is one of the mitigation tools for GHGs reduction set by the Kyoto Protocol. The CDM has two major objectives; one is to help the industrialized countries (Annex I) achieve their emission reduction targets, and two is to assist the developing countries (Non-Annex I) achieve sustainable development (SD) through greener investments. Different types of projects can be implemented as CDM projects based on the specific conditions dictated mainly by the key objectives of CDM. Currently, there are 1079 registered CDM projects in developing countries, many of which are located in Asia and Latin America. Africa has only 25 projects, of which only one is found in Tanzania (Table 1) (Salum, 2008).

Uchindile Forest Plantation is an afforestation (CDM) project under the Kilombero Forestry Company Ltd (KFC). Located in Kilombero District in the eastern part of Morogoro Region, in southeastern Tanzania. Initially, KFC belonged to EFC (Escarpment Forestry Company), a Tanzanian subsidiary of TreeFarms A/S of Norway. This project is funded by TreeFarms A/S of Norway to offer emissions reduction through carbon sequestration by increasing carbon stocks in plant biomass and soil carbon (FAO, 2004).

The project overall aim is to generate Certified Emission Reduction (CER) for export once the CDM is operational. Specific objectives are:

- To undertake a carbon sequestration project through afforestation activities contributing to the reduction of greenhouse gas effect globally.
- To promote environmental conservation.
- To facilitate socio-economic development to the community residing around the project area.

It was the intention of Escarpment Forestry Company to qualify Kilombero Forest Limited as a CDM project under the Kyoto protocol (KP) (FAO, 2004). The KFL plantation is an afforestation programme which covers an area of about 12 121 ha of land on a 99-year lease from the Tanzanian Government. To date a total of 1420 ha of *Pinus patula* and *Eucalyptus saligna/grandis* have been planted. The Kilombero plantation (owned 100 percent by Escarpment Forestry Company Ltd) was established in 1997, with large-scale planting starting in 1998. Currently it is in the final stages for certification and verification of Greenhouse gas emission and sequestration activities (COV), certification being undertaken by SGS Forestry (UK). SGS Forestry is the forestry sector specialist division, which carries out forest certification assessments worldwide since the inception of the Forest Stewardship Council (FSC) in 1994. Kilombero Forest Limited has already applied for registration with the National Climate Change Focal Point. It includes a planting programme of approximately 2,000 ha of forest per annum, over a 6-year period, until an area of 15 000 ha has been planted.

The establishment of forest plantations and promotion of community tree planting around the project area is expected to relieve pressure on the local forest resources by producing

timber, building poles and fuel wood. Environmental benefits include cleaner air and water, reduced deforestation, soil conservation and biodiversity conservation. Socio-economic benefits include rural development through the creation of employment, training, and access to schools, roads, water and other social pleasantries (FAO, 2004).

### **1.3 Objectives**

#### **1.3.1 General objective**

To estimate carbon stocks in Uchindile Forest Plantation in Kilombero District.

#### **1.3.2 Specific objectives**

- (i) To estimate biomass and carbon in *Pinus patula* and *Eucalyptus saligna* plantations.
- (ii) To estimate carbon in the plantation soil.

### **1.4 Hypothesis**

$H_0$ : *Pinus patula* and *Eucalyptus saligna* plantations do not differ significantly in carbon sequestration.

$H_1$ : *Pinus patula* and *Eucalyptus saligna* plantations differ significantly in carbon sequestration.

## CHAPTER TWO

### 2.0 LITERATURE REVIEW

#### 2.1 Carbon Sequestration Concepts

Carbon sequestration is the process of increasing the carbon content of a carbon pool other than the atmosphere (IPCC, 2000). IPCC (2000) define carbon pool as a reservoir or a system which has the capacity to accumulate or release carbon. Examples of carbon pools are forest biomass, wood products, and soils. Carbon stock, on the other hand, is defined as the absolute quantity of carbon held within a pool at a specified time.

A sink is any process, activity or mechanism which removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas from the atmosphere. A given pool (reservoir) can be a sink for atmospheric carbon if, during a given time interval, more carbon is flowing into it than is flowing out (FAO, 2000). However, the concentration of CO<sub>2</sub> and other GHGs in the atmosphere has increased by 1.3 times the pre-industrial levels and losses of biodiversity at up to 1000 times as a result of anthropogenic emissions (Kirby and Potvin, 2007).

Zhang *et al.* (2007) defined biomass as the total amount of live and inert organic matter above and below ground expressed in tons of dry matter per unit area. And thus, carbon can be converted from the biomass values using a factor of 0.5 (Zhang *et al.*, 2007; Kirby and Potvin, 2007, and Laclau, 2003). A forest stand is a community of trees, including aboveground and belowground biomass and soils, sufficiently uniform in species composition, age, arrangement, and condition to be managed as a unit (IPCC, 2000).

## 2.2 Biomass and Carbon Sequestration under Plantations Management

Forests can contribute to climate change mitigation via active management through *in-situ* increased storage, increased storage in wood product pools, or the substitution of fossil fuels by bioenergy (Seidl *et al.*, 2007). However, Silver *et al.* (2000) reported that significant amounts of carbon can accumulate in plants and soils within the first 20 years of forest re-growth. For instance in a loblolly pine (*Pinus taeda* L.) plantations in Tennessee, show the ecosystem carbon content had tripled in less than 20 years due to the increases in tree biomass (Kraenzel *et al.*, 2003).

Research done in Panama on the variation in carbon storage among tree species aged 23 years showed that managed forests can sequester an average of 335 Mg Cha<sup>-1</sup>, including all vegetation and soil carbon; above-ground biomass carbon was 235.1 Mg C ha<sup>-1</sup> and below-ground biomass carbon was 54.8 Mg Cha<sup>-1</sup> (Kirby and Potvin, 2007). Twenty years old *Tectona grandis* plantations in Panama had 120 Mg Cha<sup>-1</sup> as tree carbon and 2.6 Mg Cha<sup>-1</sup> as undergrowth (Kraenzel *et al.*, 2003). Another study in China on carbon storage by ecological service forests had a total carbon density of 181.36 Mg Cha<sup>-1</sup> for coniferous and broad-leaved mixed forest and 147.80 Mg Cha<sup>-1</sup> for a 9 years old *Pinus massoniana* forest (Zhang *et al.*, 2007).

A slash pine plantation in Brazil had a net storage of 130.7 Mg Cha<sup>-1</sup> with a mean volume of 290 m<sup>3</sup> ha<sup>-1</sup> in 10 years. This can only be achieved if narrower spacings are used, leading to higher juvenile growth rates (Nabuurs and Mohren, 1995). Another study on biomass and carbon sequestration of Ponderosa pine plantations and native cypress forests in northwest Patagonia had biomass carbon of 52.3 Mg ha<sup>-1</sup> in a 14 years old pine stand and 73.2 Mg ha<sup>-1</sup> for cypress forest, with stand volume of 148.1 and 168.4 m<sup>3</sup>ha<sup>-1</sup>, respectively.

Total carbon was 139.1 Mg ha<sup>-1</sup> and 173.2 Mg ha<sup>-1</sup> for *Pinus ponderosa* and cypress, respectively (Laclau, 2003). Lundgren (1978) reported a total biomass (above and below ground) of 299, 535, and 780 Mg DMha<sup>-1</sup> which was equivalent to 149.5, 267.5, and 390 Mg Cha<sup>-1</sup> in *Pinus patula* stand in Shume at ages 10, 20, and 30 years, respectively. These figures are not exceptionally high in comparison with production estimates from other tropical conifer plantations (Lundgren, 1978).

### 2.3 Soils and Carbon Sequestration

Carbon sequestration occurs more slowly in soil than in biomass and carbon stored in soils tends to be more resistant to sudden changes in forest management than carbon stored in biomass (Vesterdal *et al.*, 2002). Vesterdal *et al.* (2002) suggested that “nutrient-rich afforestation soils may become greater sinks for carbon in the long term”. The organic matter input to arable soil is lower than forest soil because a greater amount of the produced biomass is harvested.

A study on assessment of soil and plant carbon levels in Montane Ecuador showed that soil carbon stock in 0-30 cm depth under woody bamboo were 60.8-123 Mg ha<sup>-1</sup> (Tian *et al.*, 2007). Research done in Panama on the variation in carbon storage among tree species aged 23 years showed that total soil carbon stock in 0-40 cm depth was 45.1 Mg Cha<sup>-1</sup> (Kirby and Potvin, 2007). Another study on carbon sequestration for 14 years old Ponderosa pine (*Pinus ponderosa*) plantations and native cypress (*Austrocedrus chilensis*) forests in northwest Patagonia had soil carbon (litter included) of 86.3 Mg ha<sup>-1</sup> and 116.5 Mg ha<sup>-1</sup>, respectively (Laclau, 2003). *Tectona grandis* plantations in Panama aged 20 years had 225 Mg Cha<sup>-1</sup> as soil carbon and 3.4 Mg Cha<sup>-1</sup> as litter carbon (Kraenzel *et al.*, 2003).

However, soil carbon accumulation in plantations following afforestation is highly variable, depending mainly on the depth of sampling and the chronosequence studied (Tremblay *et al.*, 2006). The world estimates in a majority of studies, shows change in soil C content to be 2.5% per year (or 1.5 Mg ha<sup>-1</sup>yr<sup>-1</sup>). According to Tremblay *et al.* (2006), mineral soil carbon content decrease during the first 10 years following afforestation, especially during the first 5 years; then followed by a recovery, slow at the beginning but faster as the stand mature. The first period of soil carbon decrease can vary from 3 to 35 years following afforestation of fallow land. This is because in young plantations, carbon losses through soil respiration are greater than carbon inputs to soil via litterfall, and the low litterfall is due to the low production of dead biomass.

The relative importance of the carbon content in the aboveground woody vegetation and soil could vary with soil type (Thorn *et al.*, 1997). For example, on poor soils, carbon sequestration could be slower in vegetation and faster in the soil, owing to a lower growth rate of the vegetation and a lower decomposition rate of the organic matter. Also an important question about the soil carbon storage potential of plantations is the size of the contribution of decomposing stumps and roots to soil carbon over many rotations. Greater addition of C to the soil compartment may be achieved by planting deep rooted tree species as reported by Kraenzel *et al.* (2003).

#### **2.4 Forest Plantation Carbon Estimation**

Carbon estimation by direct method involve Microsoft Excel Software for calculating mean diameter at breast height (dbh), total height, basal area and stand volume. The stand volume enables the estimation of plantation biomass, then biomass is converted to carbon by multiplying with a 0.5 factor (Zhang *et al.*, 2007; Kirby and Potvin, 2007, and Laclau,

2003); and below ground biomass is 0.2 of aboveground biomass (Brown *et al.*, 1989; Brown, 1997; Kirby and Potvin, 2007). Carbon estimation by modeling approach, CO2FIX V3.1 will quantify biomass and carbon stocks in trees and soil of the plantation (Schelhaas *et al.*, 2004). The modelling approach is less laborious, less time consuming, and use few important required information for providing plantation biomass and carbon outputs. For easy use and best performance of the CO2FIX model it is crucial to have precise records and excellent keeping of forest inventory data.

## **2.5 CO2FIX V3.1 Model**

This model was developed in October, by Nabuurs (2004), in The Netherlands for the purpose of simulating carbon stocks and fluxes in trees, soil, and in case of a managed forest the wood products; as well as the financial costs, revenues and the carbon credits that can be earned under different accounting systems. This model was an improvement of CO2FIX V.2, which did not simulate carbon financial costs, revenues and credits earned under different accounting systems. CO2FIX V3.1 is an easy to use model, a user friendly tool for dynamically estimating the carbon sequestration of forestry management, agroforestry and afforestation projects (Schelhaas *et al.*, 2004). Stocks and fluxes of carbon are simulated at the hectare scale with time steps of one year. The model requires taking into account important processes like: initial biomass, growth and mortality of each functional group, and interactions within and between the functional groups.

### **2.5.1 Model structure**

The model used is a “cohort model” where each cohort is defined as a group of individual trees or as a group of species, which are assumed to exhibit similar growth, and which may

be treated as single entities within the model. Each cohort has growth, mortality and turnover and can be harvested (Schelhaas *et al.*, 2004).

## **2.5.2 Basic concepts**

### **2.5.2.1 Tree growth and biomass increment**

CO2FIX V3.1 allows two basic approaches for modeling growth of the cohorts: tree growth as a function of tree or stand age, and tree growth as a function of biomass (Schelhaas *et al.*, 2004).

### **2.5.2.2 Growth as a function of stand biomass**

In a situation where the age of the forest and/or trees is known, the growth of tree biomass is often expressed as a function of time. In case of stemwood volume, this is the Current Annual Increment (CAI). Current annual increment is the increase in volume at a particular age and is determined by annual measurements of standing volume. In dense plantations, the CAI will increase rapidly in the early years, up until competition for light, nutrients or moisture causes current annual increment to reach its peak. The decline in Current annual increment can be more rapid than the early rise. In a mature forest, the CAI is often close to zero, meaning there is no change in the total wood volume on the site from year to year (Farm and Forest Line, 2008). Stemwood increment data are most commonly available, usually in the form of yield tables.

### **2.5.2.3 Biomass growth and turnover of foliage, branches, and roots**

The biomass growth of foliage, branches and roots are expressed as fractions, relative to the growth rate of the stem biomass. These fractions are additional to the stem biomass production given as  $B_i = F_i \cdot B_s$ . Where:  $F_i$  is the relative biomass allocation coefficient

( $F_f$  for foliage,  $F_b$  for branches,  $F_r$  for roots).  $B_s$  is the growth of stem biomass.  $B_i$  is the growth of biomass ( $B_f$  for foliage,  $B_b$  for branches,  $B_r$  for roots). Thus, the total biomass is  $B_t = B_s (1 + \sum (F_i))$ . Turnover is the annual rate of mortality of the biomass component in question i.e. foliage, branches, and roots (Schelhaas *et al.*, 2004).

#### **2.5.2.4 Mortality due to senescence and competition**

In CO2FIX, the natural mortality is incorporated as a fraction of the standing biomass. For several ages, the fraction of the standing biomass that dies every year will be defined (Schelhaas *et al.*, 2004). Mortality may be high at low ages, simulating severe competition during early and dense stages. At middle ages mortality may be low, particularly in the case of managed stands. When the trees approach their maximum attainable age, mortality will increase again.

#### **2.5.2.5 Mortality due to management activities**

In CO2FIX, the mortality after logging depends on the intensity of the logging operation, expressed as the volume harvested per hectare. The initial mortality is set as an annual fraction of the standing biomass, and the impact time at various logging intensities. Mortality decreases linearly over time, reaching zero at the end of the impact time. For modeling the mortality due to logging damage, mortality as a function of biomass removed from each cohort is adopted (Schelhaas *et al.*, 2004).

#### **2.5.2.6 Interaction between cohorts (competition)**

In CO2FIX V3.1, interaction is expressed as a parameter that modifies the current annual increment as given in the stem compartment. This growth modifier describes the influence of other individuals in the same cohort or the influence of other cohorts on the growth of

the cohort in question. No competition means no growth reduction occurs at any stand density. At higher densities, competition increases and the growth modifier decreases from 1 to 0.4. This is a typical situation for many forest stands. In this study growth modifier as a function of total stand biomass ( $\text{Mg ha}^{-1}$ ) will be adopted. According to Schelhaas *et al.* (2004), in practical forestry situations, these effects are already embedded in other variables such as the growth and mortality. Therefore, the default is no competition.

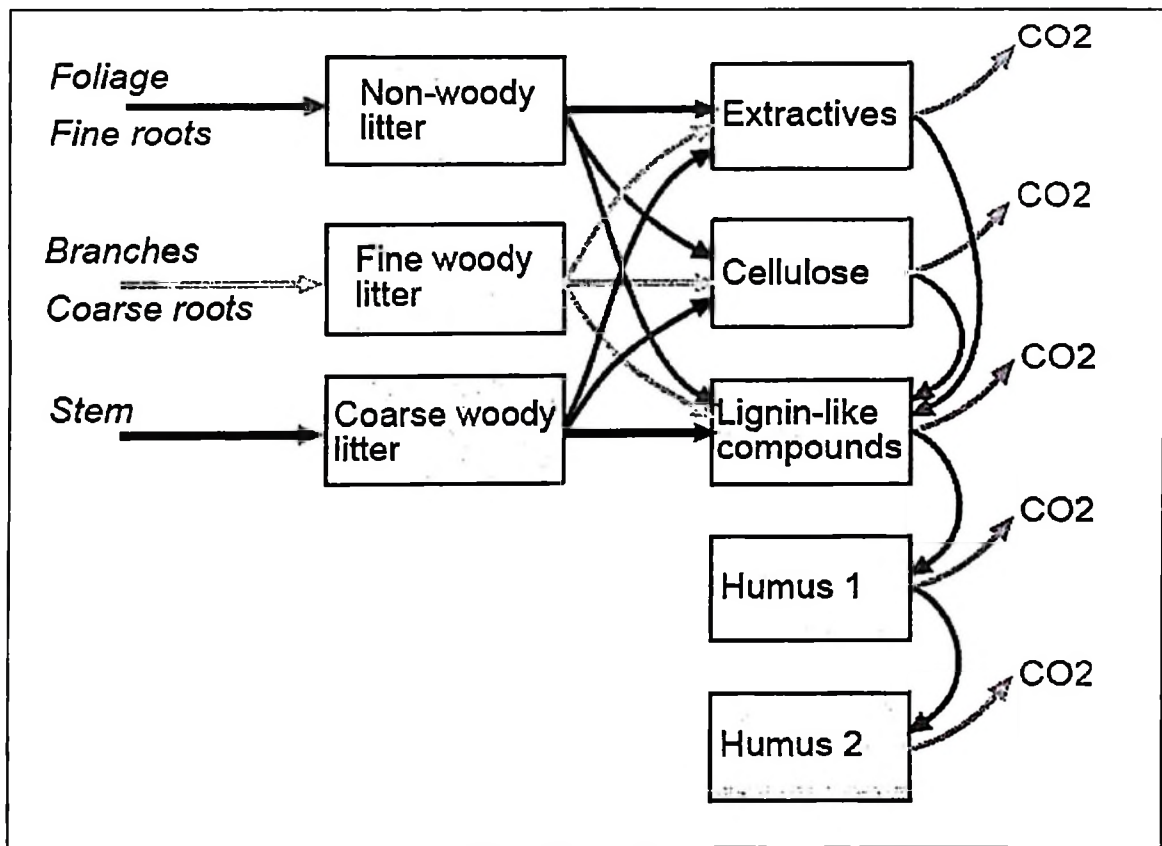
#### **2.5.2.7 Management interventions (harvesting)**

Thinning and final felling can be defined for each cohort separately. Thinning is described by the age at which the intervention takes place, intensity of the intervention (fraction of cohort biomass removed), and allocation of the biomass removed to different “raw material” classes as slash, logwood and pulpwood (Schelhaas *et al.*, 2004). In case of a management intervention, all biomass compartments are reduced according to the specified intensity. Foliage is regarded as slash and roots are regarded as litter, hence slash = 1 - (logwood + pulpwood) (Masera *et al.*, 2003).

### **2.6 Carbon Stored in Soil Organic Matter**

In CO2FIX, the dynamic soil carbon model Yasso is used (Masera *et al.*, 2003). The current version is modified to describe total soil carbon stock without distinction between soil layers (Schelhaas *et al.*, 2004). The soil module consists of three litter compartments and five decomposition compartments (Figure 1). Root litter is separated into fine and coarse roots according to the proportion between branch litter and foliage litter. Each decomposition compartment has a specific decomposition rate, determining the proportional loss of its contents in a time step. Fractions of the losses from the decomposition compartments are transferred into the subsequent decomposition

compartments having slower decomposition rates while the rest is removed from the system. The fractionation rates of woody litter and the decomposition rates are controlled by temperature and water availability. For each cohort in each scenario, the carbon stocks in each soil compartment must be initialized (Masera *et al.*, 2003). Important Yasso model parameters include values of chemical litter quality, the temperature sensitivity and initial decomposition (Schelhaas *et al.*, 2004).



Source: Schelhaas *et al.* (2004)

**Figure 1: Flow chart of the soil model. The boxes represent C compartments, and arrows represent C fluxes**

## CHAPTER THREE

### 3.0 MATERIALS AND METHODS

#### 3.1 Study Area

##### 3.1.1 Geographical location, size and altitude

Uchindile Forest Project (UFP) is developed, implemented and managed by Green Resources Ltd., owned by TreeFarms A/S, from Norway. It is located in Kilombero District that lies in the eastern part of the Morogoro Region, in southeastern Tanzania. Uchindile village, Mlimba division is about 10 km from the site of the Southern Paper Mills (SPM). It has 12,121ha of land, located between latitudes 8°39' 34" S to 8°44' 55" S and longitudes 35°23' 28" E to 35°32' 59" E, (Figure 2) at an altitude of between 1100-1437 m.a.s.l.

##### 3.1.2 Climate

Uchindile forest plantation receives an annual rainfall of about 1000mm. Its potential evaporation varies between 800-1200 mm year<sup>-1</sup>. Short rains occur during November to December, while long rains occur between March to May, but with showers extending to June and sometimes July. The mean temperature is around 16°C with the coldest months between May to September. Winds normally blows from North to East, but the prevailing winds blow from East to West during the dry season, and may blow to North West during the wet season.

##### 3.1.3 Soil

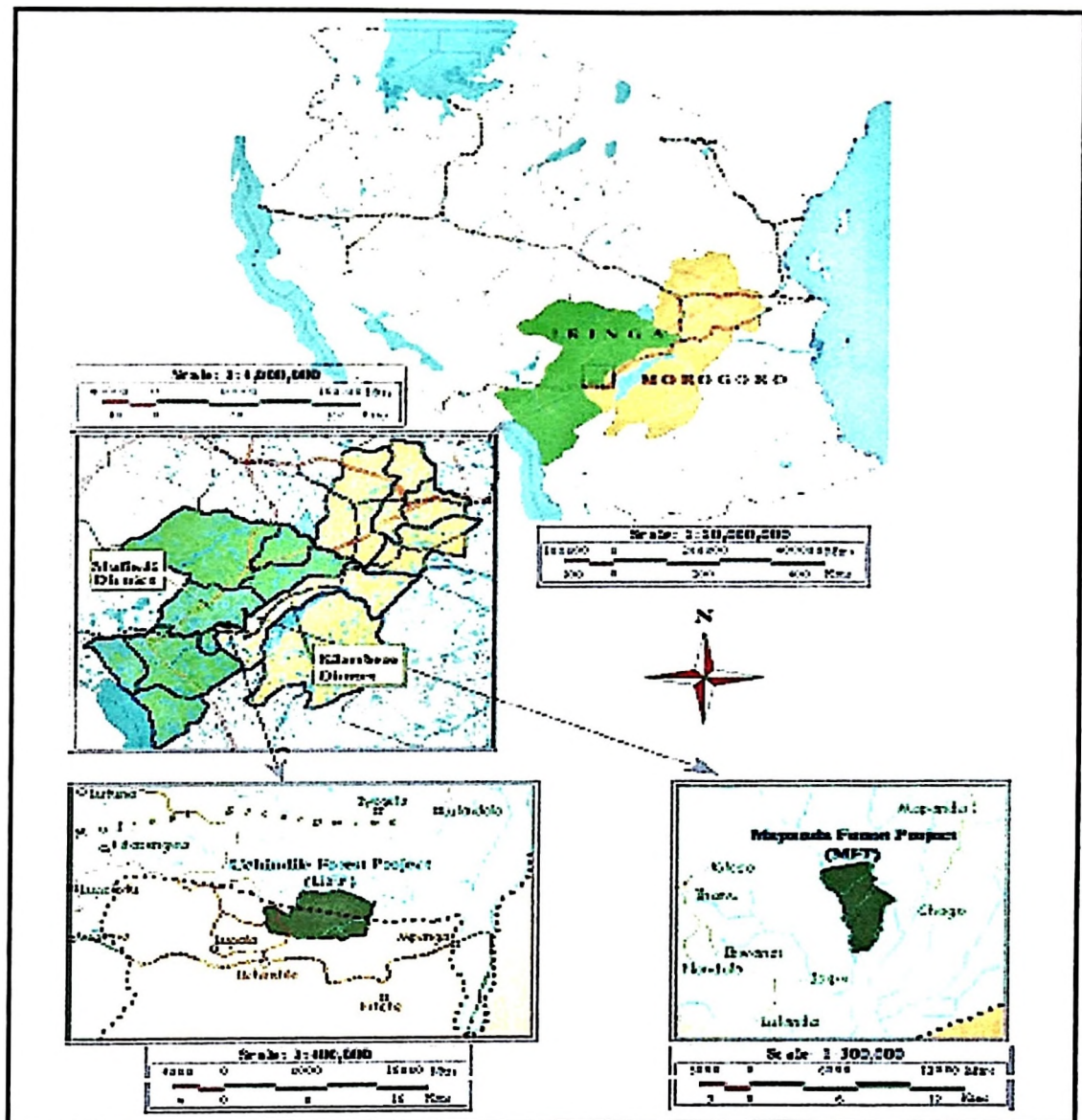
The soils are a mixture of red and yellow clays often with dark humic top soils, whose agricultural productivity rating is medium (Boger, 1980). In some areas, top soils have

been exposed to excessive annual fires and cultivation and therefore exhausted in humus content. The soils are generally red loamy sand soils (Latosolic). Soil colour ranges from red to yellow. Latosolic soils have been formed under forest and savanna vegetation in tropical and subtropical and humid to fairly dry climates. They are strongly weathered and leached, usually to great depths (Boger, 1980). Red and yellow profile colours are common to latosolic soils because of the large amounts of iron oxides from intense weathering. Supplies of plant nutrients are low in latosolic soils. The soils are easily penetrated by water and plant roots and thus they are resistant to erosion (Boger, 1980), but erosion is more realized on bare soil. Soil pH varies between 4.4 and 6.5.

#### 3.1.4 Land use and vegetation

The local communities in the neighbourhood are small-scale farmers, just producing for subsistence with limited livestock grazing. Maize is the main food and cash crop. Uchindile Forest Projects includes the following tree species: *Pinus patula*, *Eucalyptus saligna*, *Acacia melanoxylon*, *Cedrella odorata*, *Tectona grandis*, and *Grevillea robusta*. In the plantation area, there are patches of natural vegetation consisting of tree species such as *Ficus*, *Albizia*, savannah tree species and bushes. In river valleys, riverine trees can be observed dominated by *Syzygium cordatum*.

The present vegetation in the area is savannah-like communities derived from montane forest. Remnants of the dominant species include *Parinari culaterifolia*, *Catha edulis*, *Maesa lanceolata*, *Albizia gumifera*, *Prunus africana* and *Nuxia congesta*. In some patches, the vegetation is left intact to offer refuge to wildlife, improve biodiversity, protect the areas from erosion by rainwater and also protect the rivers and streams.



Source: Green Resources Limited (1984).

**Figure 2: Map locating Uchindile forest projects.**

Within the plantation, the natural undergrowth is mainly grasses with few scattered trees and shrubs. The plantation is both commercially and environmentally viable, i.e. the introduction of a new land-use (forest) into the grasslands is assumed to have no adverse impact on the existing environment.

### 3.2 Data Collection

#### 3.2.1 Stand growth data

Data were collected from two main plantation species i.e. *Pinus patula* and *Eucalyptus saligna*. For each species, stands aged 4, 6, 8, and 10 years were selected. Stratified random sampling design was adopted. Three sample plots measuring 20 m x 20 m were established in each stand. In each plot diameter at breast height (dbh) was measured using a caliper, and total stem height by a hypsometer. *Pinus patula* was planted at an espacement of 2.5 m x 2.5 m and hence each plot had 64 trees, but only 49 inner trees were measured. For *Eucalyptus saligna* each plot had 100 trees (at 2.0 m x 2.0 m spacing), and a net plot of 64 trees was used. Within each plot, four 1.0 m x 1.0 m sub-plots were randomly positioned for collection of forest litter using 1.0 m x 1.0 m wooden frame. Herbaceous plants were harvested from the sub-plots before collection of forest litter.



**Plate 1: Forest litter measurements in *E. saligna* at Uchindile Forest Plantation.**



**Plate 2: Forest litter measurements in *Pinus patula* at Uchindile Forest Plantation.**



**Plate 3: *Eucalyptus saligna* Permanent Sampling Plot at Uchindile Forest Plantation.**



**Plate 4: *Pinus patula* Permanent Sampling Plot at Uchindile Forest Plantation.**

### **3.2.2 Soil sampling**

Within each 0.04 hectare plot, four sampling points were selected at random using a random number table. At each point a mini-pit measuring 40 cm x 40 cm x 40 cm were excavated. At 0-15 cm and 15-30 cm depths, a core steel cylinder was driven on the vertical face to obtain a bulk sample for density and moisture content determination. The soil in the core was emptied into polythene bags, labeled and transported to the laboratory. From each depth, a loose soil sample was collected from each face of the pit, and mixed to form one composite sample, then sub-sampled to obtain 0.5 kg.

### 3.3 Soil Analysis

#### 3.3.1 Determination of soil bulk density, total soil C and N concentrations

In the laboratory, soil cores were weighed and soil moisture content was determined gravimetrically by oven drying a sub-sample at 105°C for 48 hours. Soil bulk density was computed as the ratio of oven dry weight to soil core volume for each sample. Soil samples for determining total soil C and N concentrations were air dried in a cool dry room before grinding and sieved through a 2-mm sieve. Soil C content was determined by the wet oxidation method of Walkey and Black (Nelson and Sommers, 1982). Total nitrogen was determined by micro-Kjeldahl method (Bremner and Mulvaney, 1982). The SOC pool was computed by multiplying the SOC concentration with bulk density and depth (Kirby and Potvin, 2007) (Appendix 3).

#### 3.3.2 Determination of carbon stock in above and below ground biomass

Tree volume was estimated by a general volume equation (Haule and Munyuku, 1994) (Appendix 1) for each tree species, based on diameter at breast height (dbh) and total height. Stem wood biomass for each age class was calculated as the product of wood density and stem wood volume, i.e. carbon mass = Volume \* stemwood BD \* correction factor (cf. = 0.5). Ringo and Klem (1980) and Idd *et al.* (1998) reported wood basic density of 410 kg m<sup>-3</sup> and 504 kg m<sup>-3</sup> for *Pinus patula* and *Eucalyptus saligna*, respectively. These values were used in this study. Carbon mass (dry matter values) were scaled to a hectare (ha) basis. Carbon content of the wood was computed by multiplying 0.5 of the total tree biomass (Zhang *et al.* 2007; Kirby and Potvin, 2007; Laclau, 2003) and below ground biomass calculated as 0.2 of aboveground biomass (Brown *et al.* 1989; Brown, 1997; Kirby and Potvin, 2007).

Forest litterfall samples were weighed to the nearest 0.1 kg, and sub-sampled. A total of 24 sub-samples of  $1\text{ kg} \pm 0.1\text{ kg plot}^{-1}$  were sent to the laboratory where they were reweighed and oven dried at 70°C to constant weight and corrected for moisture content. Live vegetation was assumed to contain 50% C on a dry weight basis. Forest litterfall was ground and analysed for total organic carbon.

### 3.4 Modelling of Carbon Sequestration

The CO2FIX V3.1 was used to quantify carbon stocks in the plantation trees and soils (Schelhaas *et al.*, 2004). The biomass equations of Lundgren (1978) for different components were applied for the *Pinus patula* data, in order to get a comparison to the CO2FIX V3.1 output results.

### 3.5 Statistical Analysis

Raw trees and soil data were processed using Microsoft Excel. Outputs obtained were, the means and standard deviations for trees survival percentages, dbh, total height, basal area, stand volume, and bulk density, % organic carbon, % total N, and C:N ratio for soil data.

For *Pinus patula* the tree biomass carbon estimated by CO2FIX V3.1 were compared with estimates from the regression equations of Lundgren (1978), using a scatter chart.

To test the hypothesis that *Pinus patula* and *Eucalyptus saligna* plantations had similar carbon sequestration, t test was used to compare the two plantation species.

## CHAPTER FOUR

### 4.0 RESULTS AND DISCUSSION

#### 4.1 Stand Data by Species and Age

Results in Table 2 indicate that, there was consistent trend of decrease in survival percentages with increase in age in *P. patula* plantations. Four-year plantations had the highest survival (87.5%) and 10-year plantations gave the lowest survival (80.2%), which is an acceptable tolerable survival limits in the plantations i.e. 80% (Anonymous, 1982). Maliondo and Chamshama (1996) reported 76% survival in six-year *P. patula* plantations at Sao Hill in Tanzania, contrary to this study average of 83.3% at Uchindile in Tanzania. That result may be attributed to moisture stresses, diseases and difficult sites in their study area (Kalaghe and Mansy, 1989). Diameter at breast height (dbh), total height, basal area and stand volume increased with age in *P. patula* plantations. Ten-year plantations gave the highest diameter at breast height (dbh), total height, basal area and stand volume. The same trend was reported by Munishi *et al.* (1996) at Kiwira in Southern Tanzania, and Kalaghe and Mansy (1989) at Sao Hill in Tanzania.

In comparing the present results with other studies, Kalaghe and Mansy (1989); Maliondo and Chamshama (1996) reported mean dbh of 9.7 cm and height of 6.5 m for six years *P. patula* plantations at Sao Hill in Tanzania. Those results were almost similar to this study result of 9.3 cm and 6.4 m, respectively for six years *P. patula* plantations at Uchindile in Tanzania. Kalaghe and Mansy (1989); Maliondo and Chamshama (1996) reported mean basal area of 7.6 m<sup>2</sup> ha<sup>-1</sup> and stand volume of 30.2 m<sup>3</sup> ha<sup>-1</sup> for six years *P. patula* plantations at Sao Hill in Tanzania. Those results were different from this study result of 8.75 m<sup>2</sup> ha<sup>-1</sup> and 56.3 m<sup>3</sup> ha<sup>-1</sup>, respectively for the same ages in *P. patula* plantations, perhaps resulting from improved management practices at Uchindile forest plantations.

Results in Table 2 indicate that, there was a clear trend of decrease in survival percentages with increase in age in *E. saligna* plantations. Survival percentages were above the acceptable tolerable survival limits in the plantations which is 80% (Anonymous, 1982). These results may be attributed to species resistance to diseases and adaptation to the difficult sites in the study area. Diameter at breast height (dbh), total height, basal area and stand volume increased with age in *E. saligna* plantations. Ten-year plantations gave the highest values of diameter at breast height (dbh), total height, basal area and stand volume.

In comparing the present results with other studies, Christie and Scholes (1995) reported mean stand volume ranging between 114-465 m<sup>3</sup> ha<sup>-1</sup> for ten-year old eucalyptus plantations in South Africa. This study result of 443 m<sup>3</sup> ha<sup>-1</sup> was within the range for the same ages in *E. saligna* plantations at Uchindile in Tanzania. Skolmen (1986) reported mean stand volume of 294 m<sup>3</sup> ha<sup>-1</sup> and dbh of 20.8 cm for five years *E. saligna* plantations at Kaumahina in Hawaii. According to Skolmen (1986) in South Africa, *E. saligna* plantations had 13 cm and 20 cm dbh at year six and ten, respectively. They are much higher than results for six years *E. saligna* plantations at Uchindile (Table 2). The results indicate that Uchindile plantation in Tanzania and South Africa were poor sites when compared to Kaumahina in Hawaii (Skolmen, 1986). The differences in volume and dbh may be attributed to better growing conditions in Hawaii in contrast to Uchindile in Tanzania and South Africa. However, Ugalde and Pérez (2001) reported average volume increments between 36 and 53 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup> on suitable sites in *E. saligna* plantations. But under less favourable conditions, e.g. in poor soils, the increments can be considerably lower.

**Table 2: Stand Data by Species and Age at Uchindile Forest Plantations, Tanzania**

Age (yr)	Survival (%)	DBH (cm)	Height (m)	Basal area (m <sup>2</sup> ha <sup>-1</sup> )	Stand volume (m <sup>3</sup> ha <sup>-1</sup> )
<i>Pinus patula</i> plantations					
4	87.5 (11.79) <sup>1</sup>	6.0 (0.71)	4.6 (0.63)	3.63 (0.17)	17.0 (0.52)
6	83.3 (11.30)	9.3 (0.34)	6.4 (0.32)	8.75 (0.72)	56.0 (0.72)
8	82.3 (12.53)	12.7 (0.41)	8.8 (0.53)	12.97 (0.59)	133.0 (0.81)
10	80.2 (13.07)	13.2 (0.11)	10.3 (0.81)	15.77 (0.05)	162.0 (0.40)
<i>Eucalyptus saligna</i> plantations					
6	86.4 (10.27)	9.9 (0.13)	14.0 (0.81)	7.50 (0.46)	105.0 (0.44)
8	85.0 (6.23)	15.5 (1.68)	15.0 (0.21)	22.13 (0.37)	332.0 (1.99)
10	84.4 (9.64)	17.7 (1.21)	17.0 (0.18)	26.08 (1.21)	443.0 (1.84)

<sup>1</sup>Mean of three replicates with standard deviations in parentheses.

#### 4.2 Bulk Density, Soil OC, Total N, and C: N Ratio in *Pinus patula* Plantations

Bulk density under *Pinus patula* plantations is given in Table 3. Bulk density did not differ significantly ( $P>0.05$ ) at 0-15 cm and 15-30 cm soil depths. Even though there was slight increase under 0-15 cm when compared to 15-30 cm depth. The slight increase may be due to more compacted soil in the top layer when compared to the subsoil, contrary to results observed by Chamshama (1994) and Ngegba (1998).

Organic carbon content in Table 3 increased slightly with plantation age at 0-15 cm depth except in eight year-old plantations, where there was a slight decrease. There was a significant ( $P<0.05$ ) difference between the two soil depth levels in year four, six and ten, but not at year eight ( $P>0.05$ ).

**Table 3: Bulk Density, Soil OC, Total N and C: N Ratio under *P. patula* Plantation at Uchindile**

Age (yr)	Soil property	Depth (cm)		Overall mean	T test
		0-15	15-30		
4	Bulk density (g cm <sup>-3</sup> )	1.38 (0.06)	1.35 (0.12)	1.37	ns
6		1.37 (0.07)	1.22 (0.19)	1.30	ns
8		1.32 (0.02)	1.21 (0.08)	1.27	ns
10		1.17 (0.15)	1.14 (0.10)	1.16	ns
4	Organic Carbon (%)	2.13 (0.21)	1.79 (0.19)	1.96	*
6		2.16 (0.31)	1.88 (0.31)	2.02	*
8		2.15 (0.15)	1.77 (0.16)	1.88	ns
10		2.52 (0.04)	1.76 (0.10)	2.14	*
4	Total Nitrogen (%)	0.13 (0.04)	0.09 (0.00)	0.11	ns
6		0.13 (0.03)	0.10 (0.03)	0.12	ns
8		0.12 (0.02)	0.10 (0.00)	0.11	ns
10		0.13 (0.02)	0.09 (0.01)	0.11	ns
4	C: N ratio	16.0 (5.85)	20.0 (2.05)	18.0	ns
6		17.0 (1.64)	19.0 (2.71)	18.0	ns
8		18.0 (4.45)	18.0 (4.18)	18.0	ns
10		19.0 (2.32)	17.0 (1.25)	18.0	ns

<sup>1</sup>Mean of three replicates with standard deviations in parentheses.

<sup>2</sup>Probability for T test: ns= not significant (p>0.05), \*= significant (p<0.05).

Total nitrogen percentages were slightly higher under 0-15 cm depth when compared to 15-30 cm depth. However, there was no significant ( $P>0.05$ ) difference between the two soil depths for all ages in *P. patula* plantations in total nitrogen. Total nitrogen percentage overall means in Table 3 were almost the same for all ages, and were between 0.11 to 0.12%. Slightly higher total nitrogen percentages under 0-15 cm depth when compared to 15-30 cm depth may be due to differences in microbial population and diversity being better in the top soil than in the subsoil (Brady, 1989; Ngegba, 1998). The low nitrogen percentage may be due to the fact that in some areas top soils have been exposed to excessive annual fires and therefore exhausted in humus content. Also red loamy sand soils (Latosolic) in the plantations may be a source of N leaching in Uchindile Forest Plantation. However, this study finding conforms to the results reported by Davis *et al.* (2007) that soil N concentrations were still lower even at year 10, these differences being significant and most apparent in the 15-30 cm layer (Table 3). These contrasting trend results may be due to higher mean C: N ratios during this period in soil layers. However, Morris (1984) reported a pronounced drop in soil nutrient levels in the Usutu forest (Swaziland) when the grassland was afforested with *P. patula*.

The C: N ratio in *Pinus patula* plantations increased slightly with age under 0-15 cm depth, it ranged from 16 to 19 for plantations aged four to ten years. But under 15-30 cm depth, C: N ratio decreased slightly with age, ranging from 20 to 17 for plantations aged four to ten years. The mean C: N ratios in Table 3 were the same for all ages (18%). There was no significant ( $P>0.05$ ) difference between the two soil depths for all ages in *P. patula* plantations in C: N ratio.

#### 4.3 Bulk Density, Soil OC, Total N, and C: N Ratio in *Eucalyptus saligna* Plantations

Bulk density under *Eucalyptus saligna* plantations is given in Table 4. Bulk density was not significantly ( $P>0.05$ ) in the plantation between soil depth, i.e. 0-15 cm and 15-30 cm. However, bulk density decreased slightly with age at 0-15 cm depth. Organic carbon content in Table 4 increased with plantation age except in 10-year old plantations, where there was a decrease. There was a significant ( $P<0.05$ ) difference between the two soil depth in year six, eight and ten in organic carbon percentages.

Total nitrogen content was slightly higher under 0-15 cm depth when compared to 15-30 cm depth, but there was no significant ( $P>0.05$ ) difference between the two soil depths for all ages in *Eucalyptus saligna* plantations in total nitrogen percentages. Total nitrogen content overall means in Table 4 were almost the same for all ages, varying between 0.10 to 0.12%. Slightly higher total nitrogen was recorded under 0-15 cm depth when compared to 15-30 cm depth, and this may be due to differences in microbial population and diversity being higher in top soils than in subsoils (Brady, 1989; Ngegba, 1998). The low nitrogen contents may be due to the fact that in some areas top soils have been exposed to excessive annual fires and therefore exhausted in humus content. Also red loamy sand soils (Latosolic) in the plantations may be a source of N leaching in Uchindile Forest Plantation (Boger, 1980; Brady, 1989).

The C: N ratio in *Eucalyptus saligna* plantations did not show a clear trend with age under 0-15 cm and 15-30 cm depth, and ranged from 17 to 18 for plantations. Results in Table 4 show that, there was no significant ( $P>0.05$ ) difference in C: N ratio between the two soil depths at all ages in *Eucalyptus saligna* plantations.

**Table 4: Bulk Density, Soil C, Total N and C: N Ratio under *Eucalyptus saligna* Plantation at Uchindile**

Age (yr)	Soil property	Depth (cm)		Overall mean	T test
		0-15	15-30		
4	Bulk density (g cm <sup>-3</sup> )	**	**	**	**
6		1.35 (0.03) <sup>1</sup>	1.35 (0.05)	1.35	ns <sup>2</sup>
8		1.29 (0.11)	1.36 (0.09)	1.33	ns
10		1.27 (0.06)	1.19 (0.04)	1.23	ns
4	Organic Carbon (%)	**	**	**	
6		1.99 (0.29)	1.55(0.24)	1.77	*
8		2.33 (0.13)	1.86 (0.04)	2.09	*
10		2.25 (0.09)	1.79 (0.04)	2.02	*
4	Total Nitrogen (%)	**	**	**	
6		0.12 (0.02)	0.09 (0.02)	0.10	ns
8		0.13 (0.01)	0.11 (0.01)	0.12	ns
10		0.13 (0.02)	0.10 (0.01)	0.11	ns
4	C: N ratio	**	**	**	
6		18.0 (4.51)	18.0 (6.18)	18.0	ns
8		17.0 (1.02)	17.0 (1.81)	17.0	ns
10		18.0 (2.23)	18.0 (1.65)	18.0	ns

<sup>1&2</sup> as defined in Table 3.

\*\*Burnt plots in the plantation.

#### 4.4 Biomass and Carbon Stored in the Two Plantation Species

Results presented in Table 5 indicate that from year four to 10 year old *P. patula* plantations with stand mean volume ranging from 16.86 to 162.43 m<sup>3</sup> ha<sup>-1</sup>, had mean biomass of 14.96 to 122.96 Mg DMha<sup>-1</sup>. This translates to 7.48 to 61.48 Mg Cha<sup>-1</sup>, and 27.45 and 225.63 Mg CO<sub>2</sub>ha<sup>-1</sup>, respectively. The high increase in biomass and carbon in the plantation is due to the fact that trees grow faster during the early years following afforestation.

Results presented in Table 5 indicate that a six to 10 years *E. saligna* plantation with stand mean volume of 104.94 to 443.43 m<sup>3</sup> ha<sup>-1</sup> had mean biomass of 87 to 367.42 Mg DMha<sup>-1</sup>. This translates to 43.5 to 183.71 Mg Cha<sup>-1</sup>, and 159.64 and 674.21 Mg CO<sub>2</sub>ha<sup>-1</sup>, respectively. However, the differences in biomass and carbon sequestration between species in the same location demonstrated that tree species have different potentials for carbon sequestration. For example, at age 4, 6, 8, and 10 years *P. patula* plantation sequestered 7.48, 21.34, 42.22 and 61.48 Mg Cha<sup>-1</sup>, equivalent to 27.45, 78.32, 154.95, and 225.63 Mg CO<sub>2</sub>ha<sup>-1</sup>, respectively. *Eucalyptus saligna* plantation on the other hand sequestered 43.5, 137.53 and 183.71 Mg Cha<sup>-1</sup>, equivalent to 159.64, 504.73 and 674.21 Mg CO<sub>2</sub>ha<sup>-1</sup>, respectively for year six, eight and ten (Table 5). This may be attributed to the basic densities used, since softwoods have lower basic densities compared to hardwoods. Also *E. saligna* was planted at a higher density, perhaps leading to higher juvenile growth rates (Nabuurs and Mohren, 1995).

In comparing the present results with other studies, Nabuurs and Mohren (1995) reported a sequestration rate of 130.7 Mg Cha<sup>-1</sup> or 479.67 Mg CO<sub>2</sub>ha<sup>-1</sup> for 10 years rotations of slash pine plantations in Brazil. This sequestration rate is higher than that estimated in this study

at a plantation age of 10 years (61.48 Mg Cha<sup>-1</sup> or 225.63 Mg CO<sub>2</sub>ha<sup>-1</sup>), probably because of species differences and more favourable growth conditions in Brazil. In addition, the study used narrow spacings, leading to high juvenile growth rates (Nabuurs and Mohren, 1995). However, results from my study fall within the of potential carbon sequestration that can be achieved by various afforestation options of 60-110 Mg Cha<sup>-1</sup> for fast growing short rotation forests on sites of moderate fertility (Nabuurs and Mohren, 1995).

In Australia, Skolmen (1983) reported a total biomass carbon of 12.5 to 45 Mg Cha<sup>-1</sup> compared to this study biomass carbon of 43.5 Mg Cha<sup>-1</sup> for *E. saligna* plantations at 6 years. This study result from *E. saligna* plantations was very close to the highest extreme Mg Cha<sup>-1</sup> reported in Australia for the same ages. Christie and Scholes (1995) reported above-ground mean biomass carbon of 26.1Mg ha<sup>-1</sup> for 10 years *E. grandis* plantation in South Africa. This sequestration rate is lower than that estimated in this study at a plantation age of 10 years (153 Mg Cha<sup>-1</sup>) in *E. saligna* plantations, probably because of species differences and more favourable growth conditions at Uchindile forest plantation in Tanzania. However, *E. saligna* literature aging 6, 8 and 10 years for comparing my results is a problem for most researches found base on rotations of 20 years and above.

From this study results, in Table 5 *E. saligna* plantations performed well in carbon sequestration (Mg ha<sup>-1</sup>) at year six, eight and ten, when compared to the same ages in *P. patula* plantations. Those results may be due to higher stand volumes in *E. saligna* plantations which had 104.94, 331.97 and 443.43 m<sup>3</sup> ha<sup>-1</sup>, contrary to *P. patula* plantations with 56.33, 133.46 and 162.43 m<sup>3</sup> ha<sup>-1</sup> respectively, at corresponding ages (see Table 2). Unfortunately, four years *E. saligna* plantations were completely destroyed by fire and thus there was no data for comparison with the *Pinus patula* plantations at that age.

**Table 5: Biomass and Carbon Stored (Mg ha<sup>-1</sup>) at Uchindile Forest Plantations**

Variable	<i>P.patula</i>				<i>E.saligna</i>		
	Years						
	4	6	8	10	6	8	10
<b><i>Biomass</i></b>							
Above-ground	12.48	35.56	70.36	102.46	72.50	229.22	306.18
Below-ground	2.48	7.12	14.08	20.50	14.50	45.84	61.24
Total biomass	14.96	42.68	84.44	122.96	87.00	275.06	367.42
<b><i>Biomass carbon</i></b>							
Above-ground	6.24	17.78	35.18	51.23	36.25	114.61	153.09
Below-ground	1.24	3.56	7.04	10.25	7.25	22.92	30.62
Total tree							
biomass C	7.48	21.34	42.22	61.48	43.50	137.53	183.71
CO <sub>2</sub> equivalent	27.45	78.32	154.95	225.63	159.64	504.73	674.21
<b><i>Soil carbon</i></b>							
Litter	1.06	1.44	1.71	2.68	1.71	2.72	2.86
Soil (0-15) cm	44.15	44.46	43.06	42.82	40.46	45.25	42.81
Soil (15-30) cm	36.08	34.13	31.99	30.97	31.48	38.09	32.10
Total soil C	81.29	80.03	76.76	76.47	73.65	86.06	77.77
Soil carbon (%)	91.5	79.2	64.5	55.4	62.80	38.60	29.70
CO <sub>2</sub> equivalent	298.33	293.71	281.7	280.64	270.29	315.84	285.41
Total carbon	88.77	101.03	118.98	137.95	117.15	223.06	261.48
CO <sub>2</sub> equivalent	325.78	370.78	436.65	506.27	429.94	818.63	959.63

#### 4.5 Soil Carbon (Mg ha<sup>-1</sup>) Stored in the Plantation Species

Results presented in Table 5 indicate that four to 10 years *P. patula* plantations had mean soil carbon of 81.29, 80.03, 76.76, and 76.47 Mg Cha<sup>-1</sup> at year 4, 6, 8, and 10, respectively. This soil carbon translates to 298.33, 293.71, 281.7, and 280.64 Mg CO<sub>2</sub>ha<sup>-1</sup>, at the respective ages. *Eucalyptus saligna* plantations had mean soil carbon of 73.65, 86.06 and 77.77 Mg Cha<sup>-1</sup>, equivalent to 270.29, 315.84 and 285.41 Mg CO<sub>2</sub>ha<sup>-1</sup> for six, eight and ten years, respectively. The trend indicated that, in both tree species there was a decrease in the soil carbon (Mg ha<sup>-1</sup>) with different plantation ages; except at year eight in *Eucalyptus saligna* plantations where there was an increase in soil carbon although it fell again at year 10 (Table 5). Also soil carbon (including litter) percentages in relation to total carbon decreased with plantation ages in both species. For instance, soil C in *Pinus patula* plantations was 92%, 79%, 65%, 55%, for year 4, 6, 8 and 10, respectively. *Eucalyptus saligna* plantations on the other hand had 63%, 39% and 30%, for year 6, 8 and 10, respectively.

The increase in soil mean carbon (Mg ha<sup>-1</sup>) at year eight may be caused by a litterfall rate higher than the decomposition rate of the organic matter in the plantation. Most studies indicate that soil carbon sequestration as a result of afforestation may not contribute much to carbon budgets during short term commitment periods (Vesterdal *et al.* 2002). Tremblay *et al.* (2006) reported that most of the carbon sequestered during the 50 years after plantation establishment was in tree biomass. However, the relative importance of the carbon content in the aboveground woody vegetation and soil may vary with soil type (Thorn *et al.*, 1997, and Vesterdal *et al.*, 2002). For example, on poor soils, carbon sequestration could be slower in the vegetation and faster in the soil owing to a lower growth rate of the vegetation and a lower decomposition rate of the organic matter.

The decrease in soil mean carbon ( $\text{Mg ha}^{-1}$ ) at year 10 may be explained by a litterfall rate lower than the decomposition rate of the organic matter, especially in young plantations. This is due to the fact that in young plantations, carbon losses through soil respiration are greater than carbon inputs to soil via litterfall, and the low litterfall is due to low production of dead biomass. According to Davis *et al.* (2007) empirical studies have mostly indicated soil carbon declines after afforestation with conifers, at least in the initial stages. Tremblay *et al.* (2006) and Davis *et al.* (2007) reported that mineral soil carbon content decreased during the first 10 years following afforestation. This is followed by a slow recovery at the beginning but faster as the stand matures. This first period of soil carbon decrease can vary from three to 35 years following afforestation of fallow land.

#### 4.6 Total Biomass and Soil Carbon ( $\text{Mg Cha}^{-1}$ ) Stored in Uchindile Forest Plantation

Results presented in Table 5 indicate that at year four to ten *P. patula* plantations had total biomass and soil carbon of 88.77, 101.03, 118.98, and 137.95  $\text{Mg Cha}^{-1}$  at 4, 6, 8, and 10 years, respectively. The total amount of carbon sequestered above is equivalent to 325.78, 370.78, 436.65 and 506.27  $\text{Mg CO}_2\text{ha}^{-1}$ , respectively. *E. saligna* plantations had total biomass and soil carbon of 117.15, 223.06 and 261.48  $\text{Mg Cha}^{-1}$  at year 6, 8, and 10, respectively. That total amount of carbon translates to 429.94, 818.63 and 959.63  $\text{Mg CO}_2\text{ha}^{-1}$ , respectively. The trend indicates that, there was an increase in the total carbon sequestered ( $\text{Mg Cha}^{-1}$ ) in the plantations with age increase in years.

From this study, the amount of  $\text{CO}_2$  equivalents to be sold for the carbon markets was: 325.78, 370.78, 436.65 and 506.27  $\text{Mg CO}_2\text{ha}^{-1}$  from *P. patula* plantations, at year 4, 6, 8 and 10, respectively. On the other hand 429.94, 818.63 and 959.63  $\text{Mg CO}_2\text{ha}^{-1}$  were from *E. saligna* plantations, at year 6, 8 and 10, at the respective ages. The two plantations

sequestered total C of 218.18, 342.04 and 399.43 Mg Cha<sup>-1</sup> at year 6, 8 and 10, respectively. This translates to 800.72, 1255.29 and 1465.91 Mg CO<sub>2</sub>ha<sup>-1</sup>, at the respective ages.

Results presented in Table 6 and Appendix 5 show that, Lundgren's equations estimated total biomass of 15.76 and 52.64 Mg DMha<sup>-1</sup> at year four and six, respectively. On the other hand CO2FIX V3.1 estimated total biomass of 62.04 and 106.76 Mg DMha<sup>-1</sup> for the same corresponding ages. At year eight and 10, Lundgren's equations estimated total biomass of 160.12 and 222.70 Mg DMha<sup>-1</sup>. The CO2FIX V3.1 model estimated total biomass of 145.48 and 187.66 Mg DMha<sup>-1</sup> for eight and 10 years. The trend indicates that, Lundgren's equations predict better biomass estimation of young plantations compared to older ones. Biomass estimates from Lundgren's equations at year four and six were close to the field estimates prepared using Microsoft Excel. On contrary, it over-estimates biomass at year eight and ten. Biomass field estimates prepared using Microsoft Excel were: 14.96, 42.68, 84.44 and 122.96 Mg DMha<sup>-1</sup> for year 4, 6, 8 and 10, respectively. On the other hand CO2FIX V3.1 outputs had over-estimated biomass at all ages when compared to field estimates prepared using Microsoft Excel.

**Table 6: Biomass CO2FIX Outputs Compared to Lundgren Regression Equations (Mg DMha<sup>-1</sup>) in Uchindile Forest, Tanzania**

<i>Pinus patula</i> plantations	Years			
	4	6	8	10
CO2FIX V3.1	62.04	106.76	145.48	187.66
Lundgren's equations	15.76	52.64	160.12	222.70
Excel calculated field data	14.96	42.68	84.44	122.96

#### 4.7 CO2FIX Outputs Compared to Field Data Results in Uchindile Forest Plantations

##### 4.7.1 CO2FIX outputs compared to field data results in *Pinus patula* plantations

Results in Figure 3 showed that the CO2FIX estimated higher biomass carbon compared to field data results calculated using Microsoft Excel, at all ages. At year four to ten the CO2FIX predicted 31.02 to 93.83 Mg Cha<sup>-1</sup>, while the field data estimated 7.48 to 61.48 Mg Cha<sup>-1</sup> for the same ages. These results indicated a big difference between the two methods in estimating biomass carbon in *P. patula* plantations. On the other hand, results in Figure 4 showed that the CO2FIX predicted lower soil carbon compared to field data estimates for the same corresponding ages. At year four to ten the CO2FIX predicted 42.91 to 41.5 Mg Cha<sup>-1</sup>, while the field data estimated 81.29 to 76.47 Mg Cha<sup>-1</sup> for the same ages. Those results indicated a big difference between the two methods in estimating biomass carbon in plantations.

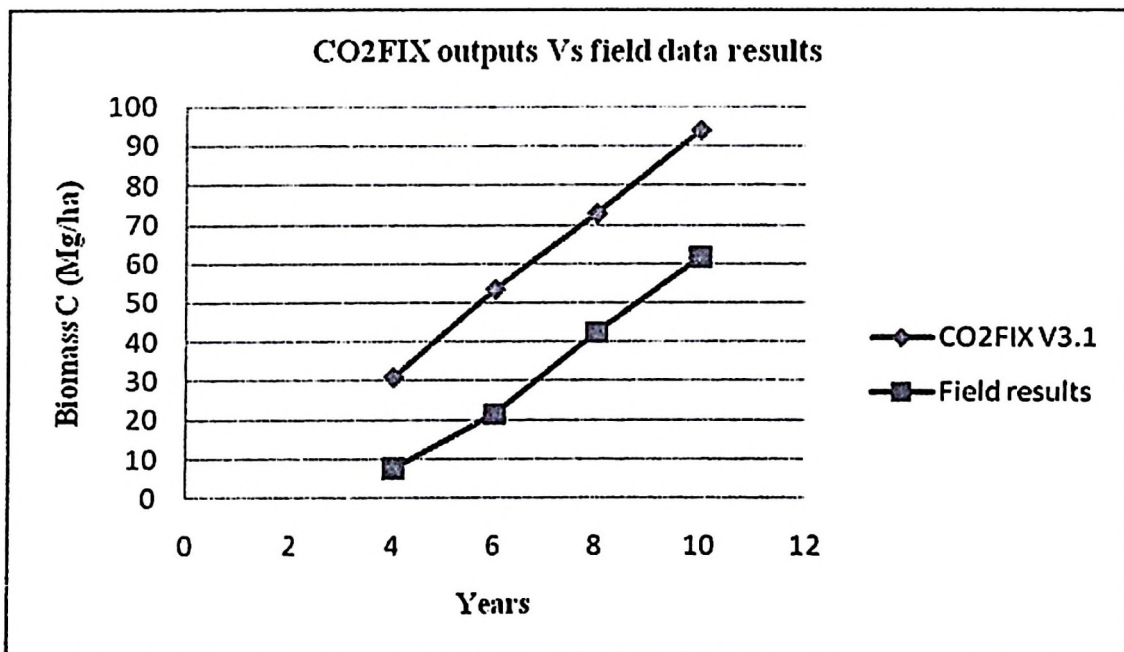


Figure 3: Biomass carbon CO2FIX outputs compared to field data results in *P. patula*.

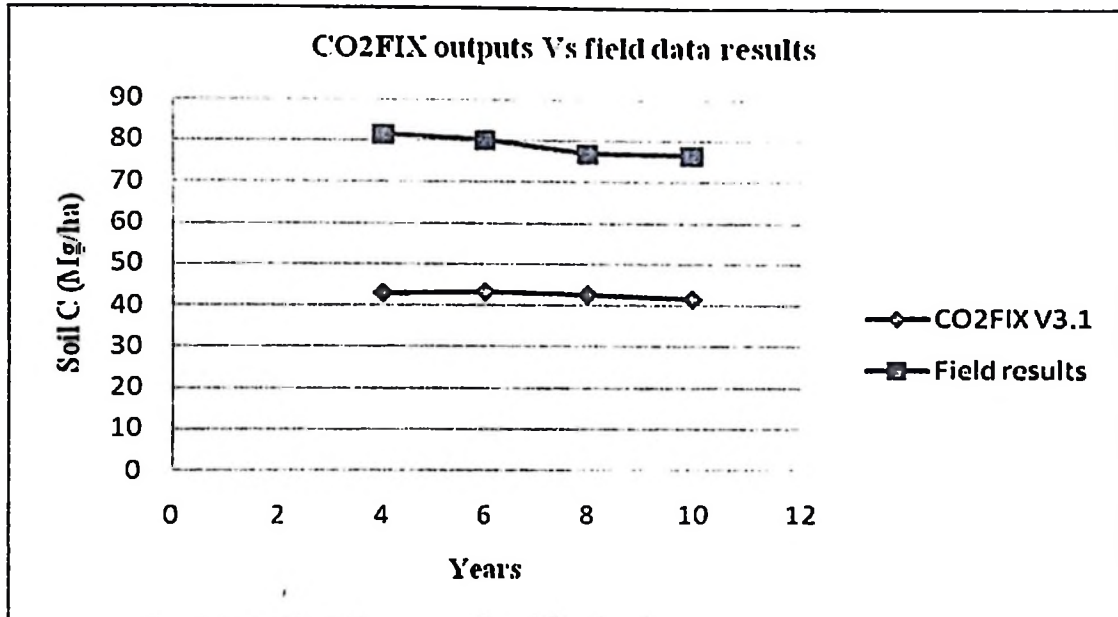
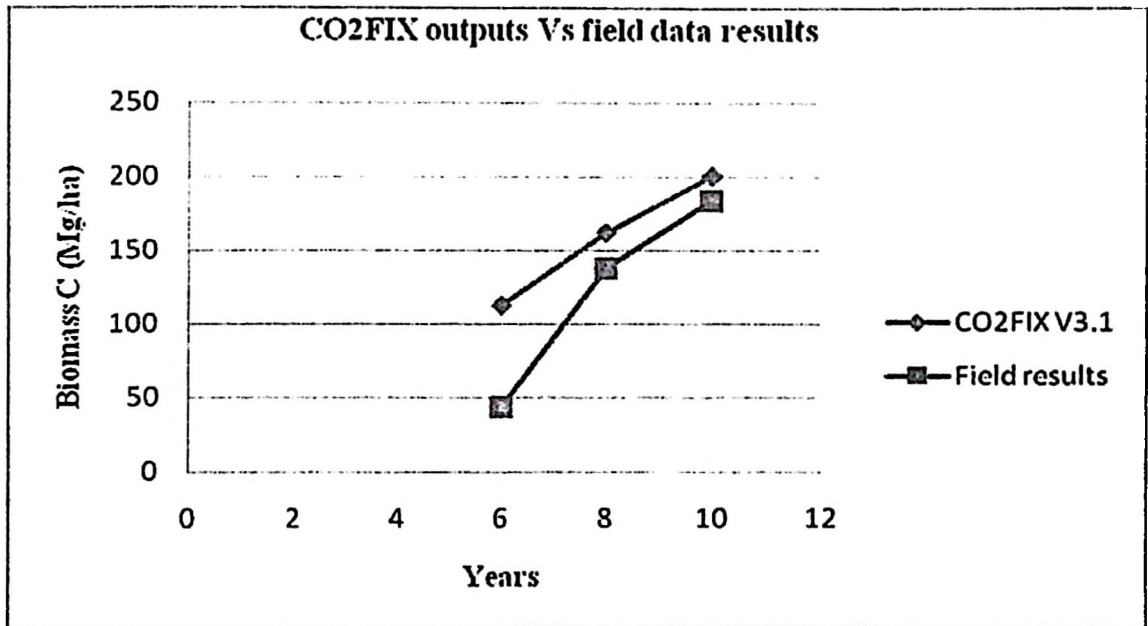


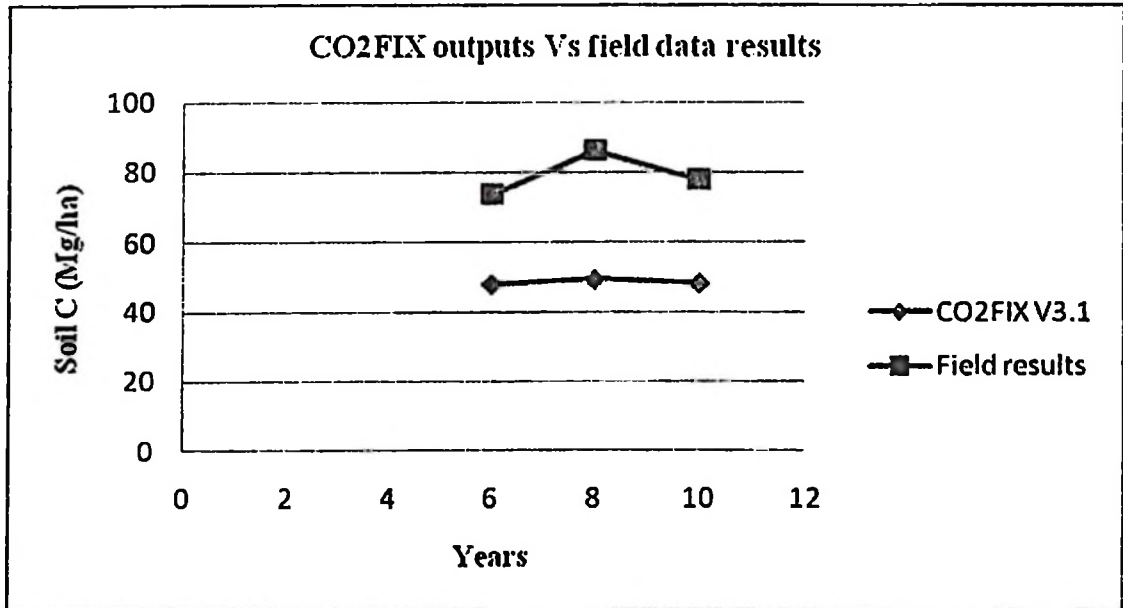
Figure 4: Soil carbon CO2FIX outputs compared to field data results in *P. patula*.

#### 4.7.2 CO2FIX outputs compared to field data results in *E. saligna* plantations

Results in Figure 5 show that the CO2FIX estimated higher biomass carbon compared to field data results estimated using Microsoft Excel, at year six to ten. From year six to ten the CO2FIX predicted 112.81 to 200.23 Mg Cha<sup>-1</sup>, while the field data estimated 43.5 to 183.71 Mg Cha<sup>-1</sup> for the same ages. Those results indicated a significant difference between the two methods in estimating biomass carbon in *E. saligna* plantations. On the other hand, results in Figure 6 showed that the CO2FIX predicted lower soil carbon compared to field data estimates for the same corresponding ages. At year six to ten the CO2FIX predicted 47.71 to 48.13 Mg Cha<sup>-1</sup>, while the field data estimated 73.65 to 77.77 Mg Cha<sup>-1</sup> for the same ages. Those results indicate a considerable difference between the two methods in estimating biomass carbon in *Eucalyptus saligna* plantations.



**Figure 5: Biomass C CO2FIX outputs compared to field data results in *E. saligna*.**



**Figure 6: Soil carbon CO2FIX outputs compared to field data results in *E. saligna*.**

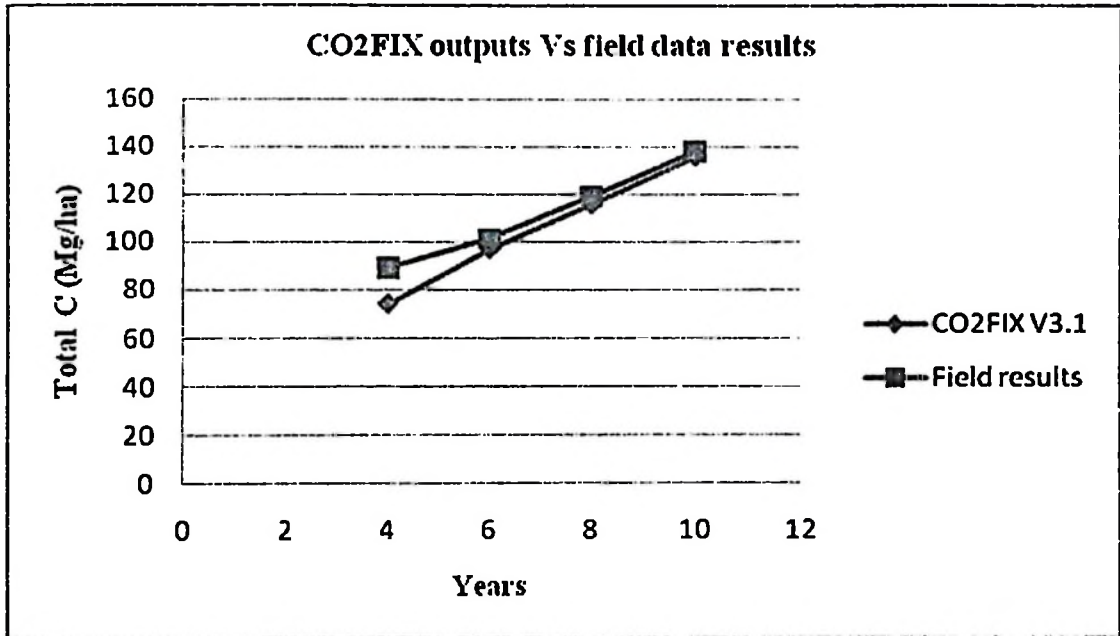
#### 4.8 CO2FIX V3.1 Outputs and Field Data Results Total Carbon Estimates

##### Comparison

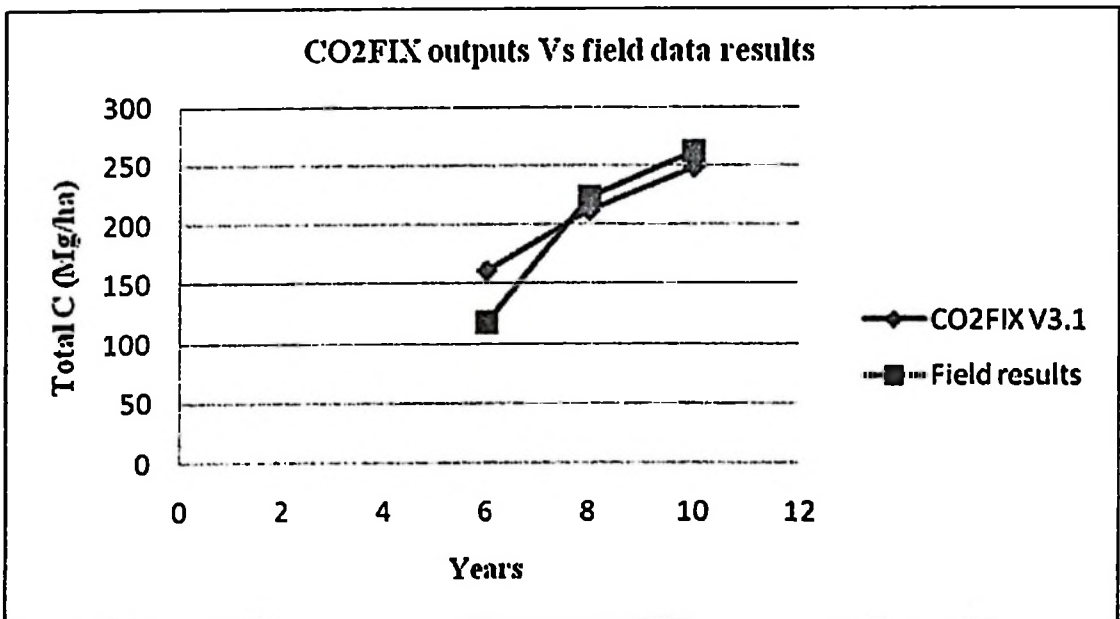
Results in Figure 7 showed that the CO2FIX estimated lower total carbon, only at year four compared to field data estimates; the remaining ages were very close to the field data results. For instance at year 6, 8 and 10 the CO2FIX predictions were 96.63, 115.26 and 135.33 Mg Cha<sup>-1</sup> while the field data estimates were 101.03, 118.98 and 137.95 Mg Cha<sup>-1</sup>, respectively for the same ages. Those results indicate a good performance of the CO2FIX V3.1 model in estimating carbon stocks in *P. patula* plantations, especially at old ages. On the other hand results in Figure 8 show that the CO2FIX estimated higher total carbon, only at year six compared to field data estimates. For eight and ten years, the estimates were close to the field data results. For instance, at year eight and ten the CO2FIX predictions were 211.52 and 248.36 Mg Cha<sup>-1</sup>, while the field data estimates were 223 and 261.48 Mg Cha<sup>-1</sup>, respectively. Those results indicate a good performance of the CO2FIX V3.1 model in estimating carbon stocks in *P. patula* plantations, (Figure 7) especially in old ages as clearly indicated also in the *E. saligna* plantations (Figure 8).

The CO2FIX V3.1 model had proved to be a good tool in estimating carbon stocks. Appendix 6 and 7 show a maximum increase in biomass, soil and total carbon at the end of every 25 years of the plantation rotation. This trend is attributed to thinned stems, branches, foliage and roots which should be included in the carbon stocks estimation by CO2FIX V3.1 model. According to this study the trend indicates that, CO2FIX V3.1 under-estimate soil carbon but over-estimate biomass carbon in tree biomass (Appendix 6 and 7). Total plantation carbon stocks predicted by CO2FIX V3.1 were close or very close to the field data estimates especially in old plantations. Also poor predictions at year four

and six may be attributed to the model weakness of favouring old plantations rather than young ones (Figure 7 and 8).



**Figure 7: Total carbon CO2FIX outputs compared to field data results in *P. patula*.**



**Figure 8: Total carbon CO2FIX outputs compared to field data results in *E. saligna*.**

In testing the hypothesis that *P. patula* and *E. saligna* plantations had similar carbon sequestration, Table 7 results indicate a very strong significant difference between the two species in carbon stocks at all tested ages ( $P < 0.05$ ). *E. saligna* plantations sequestered ( $P < 0.05$ ) significantly higher amounts of carbon compared to *P. patula* plantations. Carbon stored by *E. saligna*, excluding soil C ranged between 67 to 74.9% from year six to ten. While, carbon stored by *P. patula*, excluding soil C ranged between 25.1 to 33% for the respective ages. This may be attributed to higher stand volumes attained in *E. saligna* plantations in comparison to *P. patula* for the same corresponding ages (see Table 2).

**Table 7: Species Mean Carbon Stocks in Uchindile Forest Plantations, Tanzania**

Age (yr)	Species	Mg Cha <sup>-1</sup>	P-value
6	<i>Pinus patula</i>	21.33 (0.49)	
	<i>Eucalyptus saligna</i>	43.47 (1.22)	0.001 <sup>1</sup> ***
8	<i>Pinus patula</i>	42.22 (3.0)	
	<i>Eucalyptus saligna</i>	137.53 (7.0)	0.001 ***
10	<i>Pinus patula</i>	61.54 (0.67)	
	<i>Eucalyptus saligna</i>	183.71 (10.74)	0.001 ***

<sup>1</sup> as defined in Table 3

## CHAPTER FIVE

### 5.0 CONCLUSION AND RECOMMENDATIONS

#### 5.1 Conclusion

- (i) The study did not support the hypothesis that *P. patula* and *E. saligna* plantations have similar carbon sequestration potential. Eucalyptus plantations had significantly higher carbon storage than *P. patula* plantations.
- (ii) In this study *E. saligna* plantations sequestered 1.15 to 1.89 times amounts of carbon in comparison to the *P. patula* plantations at year six to ten.
- (iii) The two plantations sequestered total C of 218.18, 342.04 and 399.43 Mg Cha<sup>-1</sup> at year 6, 8 and 10, respectively. This translates to 800.72, 1255.29 and 1465.91 Mg CO<sub>2</sub>ha<sup>-1</sup>, at the respective ages.
- (iv) The CO2FIX V3.1 proved to be a good tool in estimating carbon stocks especially in plantations older than six years, but Lundgren's regression equations are better predictors of carbon stocks of forest plantations at six years or younger.
- (v) According to this study, the CO2FIX V3.1 under-estimates soil carbon and over-estimates biomass carbon; but the total carbon stocks prediction in the plantation is exactly or approximately very close to calculated field data results.

## 5.2 Recommendations

- (i) From this study, it is recommended that fast growing tree species like *E. saligna* that were found to sequester higher amounts of carbon to be planted as a mitigation option for offsetting carbon dioxide emissions to the atmosphere.
- (ii) The findings of this study indicate that, the CO2FIX V3.1 should be used to predict total plantation carbon stocks of stands at or above eight years but not at four to six years. On the other hand, Lundgren's regression equations gave better predictions for four to six-year old plantations, but seemed to exaggerate the amount of carbon stocks in stands older than six years.
- (iii) The amounts of atmospheric carbon dioxide in the study area were 800.72, 1255.29 and 1465.91 Mg CO<sub>2</sub>ha<sup>-1</sup> at year 6, 8 and 10, respectively. This was legible to be sold for the CDM market.

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## APPENDICES

### Appendix 1: General tree volume formula

Volume for *P. patula*:  $V_i = 0.54 g h_i$

Volume for *E. saligna*:  $V_i = 0.45 g h_i$

Where:  $V_i$  = the volume of the  $i^{\text{th}}$  tree ( $\text{m}^3$ )

$h_i$  = the total height of the  $i^{\text{th}}$  tree (m)

$g$  = the tree basal area ( $\text{m}^2$ )

0.54 and 0.45 = tree form factors as indicated in the formula.

### Appendix 2: Lundgren (1978) biomass regression equations

For *Pinus Patula*  $\sqrt[3]{y_1} = 0.314x - 0.146$  ( $r = 0.993$ );  $y_1 = \text{stem Kg/tree d.w}$

$\sqrt[3]{y_2} = 0.191x + 0.170$  ( $r = 0.961$ );  $y_2 = \text{branch Kg/tree d.w}$

$\sqrt[3]{y_3} = 0.126x + 0.493$  ( $r = 0.948$ );  $y_3 = \text{foliage Kg/tree d.w}$

$\sqrt[4]{y_4} = 0.0827x + 0.024$  ( $r = 0.978$ );  $y_4 = \text{cones Kg/tree d.w}$

$\sqrt[3]{y_5} = 0.158x + 0.185$  ( $r = 0.989$ );  $y_5 = \text{root Kg/tree d.w}$

Where:  $x = \text{tree dbh (cm)}$

### Appendix 3: Equation for computing soil organic carbon

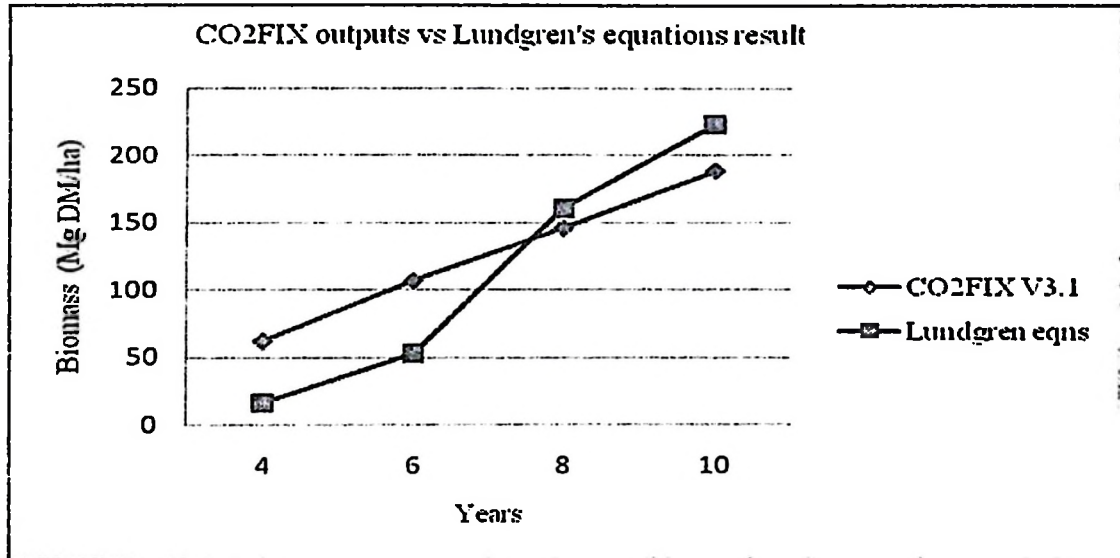
Soil carbon pool ( $\text{Mg ha}^{-1}$ ) layer = Total soil carbon (% OC) layer x soil bulk density ( $\text{g cm}^{-3}$ ) layer x depth (cm) layer.

**Appendix 4: Stand volume, biomass and carbon (Mg ha<sup>-1</sup>) stored at Uchindile forest plantation as predicted by CO2FIX V3.1 model**

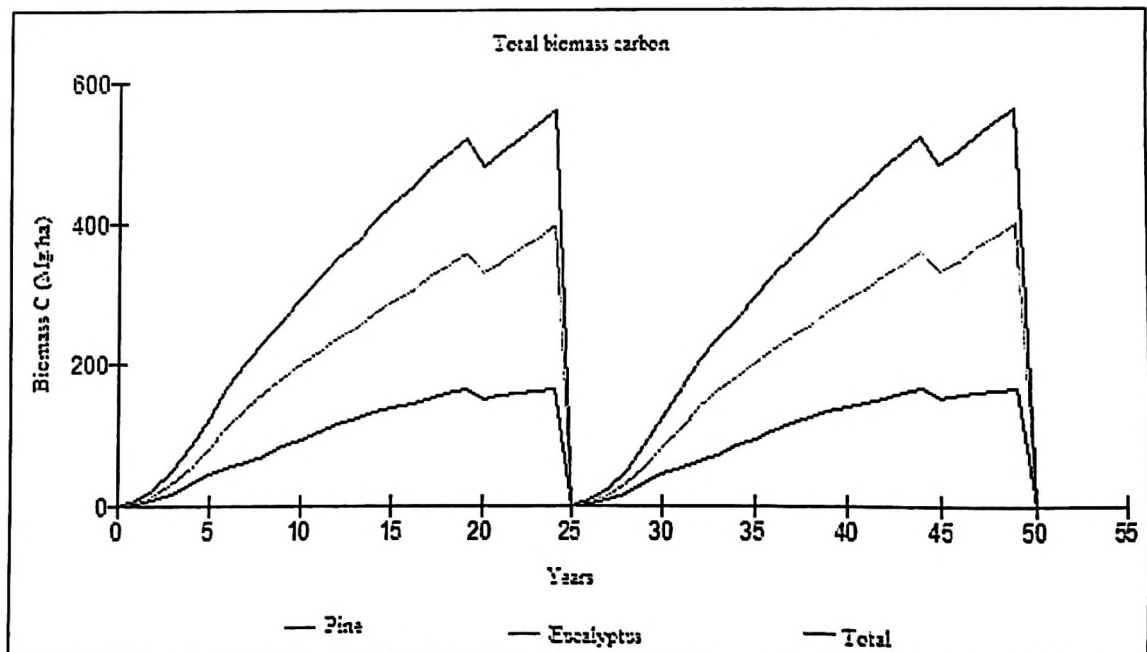
Variable	<i>P.patula</i>				<i>E.saligna</i>			
	Years							
	4	6	8	10	4	6	8	10
Stems volume	89.58	158.85	227.42	303.75	160.47	337.01	495.51	621.60
CAI (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	35.83	34.24	36.11	38.38	64.19	96.29	73.57	59.54
<i>Biomass</i>								
Stems	36.72	65.12	93.24	124.54	80.88	169.86	249.74	313.28
Foliage	7.46	8.94	7.98	7.42	5.34	7.28	5.56	4.5
Branches	11.06	20.20	27.30	34.40	9.68	20.5	28.38	33.48
Total AG	55.24	94.26	128.54	166.36	95.9	197.64	283.68	351.26
Roots	6.80	12.5	16.94	21.30	11.74	27.98	40.8	49.2
Total biomass	62.04	106.76	145.48	187.66	107.64	225.62	324.48	400.46
<i>Biomass carbon</i>								
Stems	18.36	32.56	46.62	62.27	40.44	84.93	124.87	156.64
Foliage	3.73	4.47	3.99	3.71	2.67	3.64	2.78	2.25
Branches	5.53	10.10	13.65	17.20	4.84	10.25	14.19	16.74
Total AG	27.62	47.13	64.27	83.18	47.95	98.82	141.84	175.63
Roots	3.40	6.25	8.47	10.65	5.87	13.99	20.40	24.60
Total biomass carbon	31.02	53.38	72.74	93.83	53.82	112.81	162.24	200.23
CO <sub>2</sub> equivalent	113.84	195.90	266.95	344.35	197.52	414.01	595.42	734.84
<i>Soil carbon</i>								
Total soil C	42.91	43.25	42.52	41.50	44.52	47.71	49.28	48.13
CO <sub>2</sub> equivalent	157.47	158.72	156.04	152.30	163.38	175.09	180.85	176.63
Total carbon	73.93	96.63	115.26	135.33	98.34	160.52	211.52	248.36
CO <sub>2</sub> equivalent	271.32	354.63	423.00	496.66	360.91	589.11	776.28	911.48

AG is the above-ground.

Appendix 5: CO2FIX V3.1 outputs against Lundgren's regression equations biomass results ( $\text{Mg DMha}^{-1}$ ) in *Pinus patula* plantations



Appendix 6: Total biomass carbon ( $\text{Mg ha}^{-1}$ ) stored at Uchindile forest plantation predicted by CO2FIX V3.1



**Appendix 7: Total soil carbon (Mg ha<sup>-1</sup>) stored at Uchindile forest plantation predicted by CO2FIX V3.1**

