GROWTH PERFORMANCE, WATER USE AND WOOD PROPERTIES OF EUCALYPT CLONES IN TANZANIA

NANCY ELIAD PIMA

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ABSTRACT

This study was conducted to determine growth performance, water use and wood properties of Eucalypt clones in Tanzania. Eucalypt clones of *Eucalyptus grandis x E. camaldulensis* (GC), *E. grandis x E. urophylla* (GU), *E. grandis x E. tereticornis* (GT) growing in Lushoto, Kwamarukanga, Kibaha and Tabora sites were studied. Growth performance, water use and wood properties data were collected at the age of 8 to 10 years. Data on growth performance were analysed using SAS Software and subjected to ANOVA using treatment means. Water use data were analysed using sap flow tool software. Wood properties data were analysed using SAS Software and subjected to ANOVA using treatment means. Significant clones' means were separated using Duncan's Multiple Range Test. Results revealed significant ($p<0.05$) difference in survival, Dbh, height, basal area, volume and biomass between clones. Significant ($p<0.05$) difference in water use was observed between clones. Results revealed that GC167, GC15 and GC940 had average water uses of 14, 7 and 5 L day^{-1} respectively in wet season and 11, 9 and 8 L day^{-1} respectively in dry season. Significant ($p<0.05$) differences in fibre length, modulus of elasticity and shear strength were observed between clones from all sites. No significant differences between clones were observed in wood density, modulus of rupture, compression and cleavage strength. The study concludes that some Eucalypt clones showed good survival, growth, basal area, volume and biomass in respective sites. Wood properties for the studied clones meet the minimum requirements needed for pulp and paper production, fuel wood and for structural applications. This study recommended the following clones, GC 581, GC 584 and GU 608 for Lushoto, GC 15, GC 167 and GC 940 for Kibaha, GC 514, GT 529 and GC 940 for Kwamarukanga and GC 15, GC 584 and GC 940 for Tabora site to be considered for planting in areas with climatic conditions similar to the sites where they were tested. The clones should be considered as sources of raw material for pulp and paper production, charcoal, timber for furniture and for structural applications.

DECLARATION

I, NANCY ELIAD PIMA, do hereby declare to the SENATE of Sokoine University of Agriculture that this thesis is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

______________________ ______________________

Nancy Eliad Pima Date

(PhD Candidate)

The above declaration is confirmed by:

______________________ ______________________

Prof. S. A. O Chamshama Date

(Supervisor)

______________________ ______________________

Prof. S. Iddi Date

(Supervisor)

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DEDICATION

This work is dedicated to my parents: Eliad Pima and Jane Semng'indo who due to their love shaped me into who I am; to my beloved husband Joshua Maguzu, and my children Gaudensia and Geofrey, to my brothers and sisters.

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LIST OF ABBREVIATIONS AND ACRONYMS

AIC	Akaike Information Criterion
ANOVA	Analysis of variance
BA	Basal area
BD	Basic density
BS	British Standards
cm	Centimetre
cm^3	Centimetre cubic
COSTECH	Tanzania Commission for Science and Technology
CS	Compression strength
Dbh	Diameter at breast height
DMRT	Duncan Multiple Range Test
FPL	Forest Products Laboratory
GC	*Eucalyptus grandis* x *Eucalyptus camaldulensis* clone
GT	*Eaucalyptus grandis* x *Eucalyptus tereticornis* clone
GU	*Eucalyptus grandis* x *Eucalyptus urophylla* clone
ha	Hectare
HPV	Heat Pulse Velocity
hr	Hour
HRM	Heat Ratio Method
Ht	Height
i.e.	That is
ISO	International Organization for Standards
ITTO	International Tropical Timber Organization
KFMP	Kenya Forestry Master Plan

KFS	Kenya Forest Service
kg m^{-3}	Kilogramme per cubic metre
L	Litres
m	Metre
m^3	Metre cubic
MAI	Mean Annual Increment
m.a.s.l	Metres above sea level
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
NGO	Non Governmental Organisation
NLP	Non Linear Programming
^oC	Degree Celsius
r	Correlation coefficient
R^2	Coefficient of determination
SAS	Statistical Analysis System
SUA	Sokoine University of Agriculture
t	Tonnes
TaFF	Tanzania Forest Fund
TAFORI	Tanzania Forestry Research Institute
yr	Year

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information

Eucalyptus is one of the diverse genera of flowering plants in the world. They are generally long-lived, evergreen species belonging to the angiosperm family Myrtaceae (Ladiges *et al.,* 2003). Globally, the genus has now been recognized to comprise more than 800 species and an unknown number of hybrids and varieties (Boland *et al.*, 2006; Zegeye, 2010) mostly native to Australia, while a very small proportion are found in adjacent parts of New Guinea, Philippines, Timor and Indonesia (Brooker *et al.,* 2002; Louppe *et al.,* 2008; Oballa *et al.,* 2009). The genus has many favourable characteristics including fast growth rates, wide adaptability to soils and climate, easy management through coppicing and valuable wood properties (Eldridge *et al.*, 1993; Myburg *et al.,* 2006).

The *Eucalyptus* species is among the most widely cultivated forest trees in the world (Ladiges *et al.,* 2003; Liu and Li, 2010; ICFRE, 2010; Delgado-Matas and Pukkala, 2011). It is estimated that there are over 22 million hectares (ha) (Myburg *et al.,* 2006; Nichols *et al.,* 2010) of Eucalypt plantations worldwide, of which over 10 million ha are in the tropics (Turnbull, 1999; FAO, 2006; Delgado-Matas and Pukkala, 2011). Over 2 million ha of Eucalypt plantations are in Africa where *E. grandis* and *E. camaldulensis* are the most planted species (FAO, 2006). In Tanzania, the area under *Eucalyptus* species is estimated to be 25 000 ha (Munishi, 2007) of which 4,665 ha are grown by Government and the rest are grown by the Private Sector and small-scale farmers (Ngaga, 2011). *Eucalyptus* species are fast growing trees, with a short rotation and produce better quality wood and more uniform stands than most indigenous trees (Turnbull, 1991;

Bouillet *et al*., 2004). The direct benefits of Eucalypts include raw materials for pulp, fuel wood, plywood, transmission poles, building materials, fencing posts, railway sleepers, windbreaks and ornamentals while indirect benefits include environmental services such as carbon sequestration and climate amelioration (He and Barr, 2004; Hajari *et al.,* 2006).

Eucalypt clones have been considered as one of the solutions to meet the need for forest products in Tanzania. Eucalypt clones were introduced from Mondi South Africa to East African countries of Tanzania, Kenya and Uganda during the period 1997 to 2003. In Tanzania, the clones were introduced in 2003 through Tanzania Forestry Research Institute (TAFORI) as experimental plots to test their adaptability in the Tanzanian environment before large scale planting. Experiments started in 2004 using *Eucalyptus grandis* x *E. camaldulensis* (GC) clones, *E. grandis* x *E. urophylla* (GU) clones*,* and *E. grandis* x *E. tereticornis* (GT) clones. These clones combine desired traits of two species. While *E. grandis x E. camaldulensis* (GC) combines good growth and drought tolerance, *E. grandis x E. urophylla* (GU) combines good growth and disease resistance and *E. grandis x E. tereticolnis* (GT) combines good growth and rooting ability. The clones are preferred for their fast growth with a short rotation, wide adaptability to site conditions, produce better quality wood and more uniform stands than most indigenous trees. Wood of Eucalypt clones is used in many applications in house construction, production of fuel wood, poles, telecommunication posts, fencing posts, electricity transmission poles, pulp and timber (Oballa *et al.,* 2009). Eucalypt plantations/woodlots contribute significantly to reducing the wide gap between demand and production of wood in the shortest possible time (Oballa *et al.* 2009), thus reducing pressure on the few remaining natural forests (Mwangingo and Msangi, 2004).

The productivity of Eucalypt clones varies with clonal-interaction, site, climate and silvicuture. In the tropics, mean annual increment (MAI) vary between 30 and 50 m^3 ha^{-1} yr^{-1} and reach up to 100 m^3 ha^{-1} $yr^{-1}$for the best clones on the best sites (Eldridge *et al.,* 1993; Ugalde and Pérez, 2001; Lal, 2003). In China, the productivity of up to 70 m^3 ha^{-1} yr^{-1} was reported which suggests that there is great potential for improving productivity of Eucalypt plantations elsewhere (Daping, 2003). Thus, fast growth rates, wide adaptability to environmental conditions and high productivity of *Eucalyptus* species have contributed to the great interest in many countries outside its native range (Myburg *et al.,* 2006).

However, *Eucalyptus* is one of the tree species that have invoked a lot of debate, especially regarding its suitability for planting in many sites (Mbinga, 2009; Kirongo *et al.,* 2010). It is alleged to deplete underground water resources and to show allelopathic effects when grown with other crops, allegations which are contested in some professional circles (Olbrich *et al.,* 1993; Kallarackal and Somen, 1997; Jagger and Pender, 2000; Soares and Almeida, 2001; Albaugh *et al.,* 2013). Studies in India (Calder *et al.,* 1992) and in South Africa (Dye, 1996) indicate that when water resources are limited, the area, location and management of plantations must be carefully considered to avoid conflict with other water users. Dye *et al.* (2004) in Brazil reported mean daily water use ranging from 30 to 64 L day^{-1} in 1.5 – 7 year old stands of *E. grandis* × *camaldulensis* hybrid clones growing on more productive sites, and from 15 to 34 L day^{-1} for the less productive sites. Sunder (1993) and Keitel and Adams (2009) reported water use ranging from 20 to 68 L $day^{-1}$for *E. camaldulensis* and *E. victrix*.

On the other hand, the main focus in tree breeding programme are traits related to wood properties for the development of improved varieties for pulp and paper production as well as wood for energy or timber production. Wood basic density is one of the most often studied wood quality trait because it determines the economic value and is under high degree of genetic control (Sprague *et al.,* 1983). It affects properties of various wood products such as pulp and paper, wood strength and wood quality (Zobel and van Buijtenen, 1989). The suitability of wood for various uses is determined by its properties. Some of the important properties for end use include mechanical properties. Mechanical properties of wood are an expression of its behaviour under applied forces. It refers to the ability of the material to resist external loads or forces tending to cause change in its size and alteration of its shape (FPL, 2010). The uses to which wood is put require the ability to resist loads and thus it is appropriate to examine the behaviour of wood when subjected to various forces. They are the most important characteristics of wood products for structural applications. A structural application is any use where strength is one of the primary criteria for selection of material. Structural uses of wood and wood products include tie beams, purlins in house construction, floor joists and rafters in wood-frame housing, power line transmission poles, plywood roof sheathing and sub-flooring and glue laminated beams in commercial buildings (Haygreen and Bowyer, 1989).

1.2 Problem Statement and Justification

1.2.1 Problem statement

Although there is a considerable area in Tanzania planted with Eucalypt clones, little research has been done on the growth performance of these clones. Several studies have reported significant growth performance of Eucalypt clones in Kenya and elsewhere (Oballa *et al.,* 2005; Arya *et al.,* 2009). Results from these studies show that Eucalypt clones have similar or better growth than their parents and significant differences in growth between hybrid clones may be attributed to their genetic differences as well as environmental factors like soil pH, mean annual rainfall and mean temperature.

In Tanzania, a study by Msangi *et al.* (2009) reported growth and survival of 4 year old Eucalypt clones. The results showed significant survival and growth difference within and between sites. The results also showed species site specific performance where GCs and GT hybrids survived and performed well in low land areas.

On the other hand, *Eucalyptus* species have been critisised in several countries for consuming excessive amounts of water (Calder *et al.,* 1992; Kallarackal and Somen, 1997; Soares and Almeida, 2001; KFS, 2009; Albaugh *et al.,* 2013), and drying out the sub-soil, consequently lowering the water table (Srivastava *et al.,* 2003). The worries have persisted even upto now in tropical countries such as Ethiopia, Rwanda, Kenya, Tanzania and Uganda (Nduwamungu *et al*., 2007). Although there has been a number of robust scientific studies undertaken on water use by Eucalypts (Calder, 1992; Calder, 1999; Lima, 2011), variation of species and environments means generalised conclusions cannot be drawn. Lack of adequate data in Tanzanian conditions to justify conclusive decisions on Eucalypts water use is a major constraint to solutions on Eucalypts planting.

In addition, the main focus in tree breeding programmes is on traits related to wood properties for the development of improved varieties for pulp and paper as well as wood for energy or timber production (Gion *et al.,* 2011). However, several studies have reported variation of physical properties of Eucalypt clones and other *Eucalyptus* species. For example, Muga *et al.* (2009) in Kenya and Turinawe *et al.* (2014) in Uganda reported that wood of Eucalypt clones had the same or higher density and fibre length values as their parents. Veenin *et al.* (2005) in Thailand, Pereira *et al.* (2012), Jorge *et al.* (2000) in Brazil and Sadegh and Kiaei (2011) in Iran reported variations in wood basic density and fibre length of *E. globulus* and *E. camaldulensis*. The authors found that wood density and fibre length values increased along the axial direction from bottom to the top of the tree. On the other hand, the initial decline of wood density between the 5 to 15% height levels before the increase upwards was also reported for some species, namely *E. globulus* and *E. nitens* (Raymond and Mineri, 2001), *E. globulus* (Quilhó and Pereira, 2001) and *E. grandis x E. urophylla* hybrid (Quilhó *et al.,* 2006). However, there are no studies on the variation of wood basic density and fibre length within and between Eucalypt clones grown in Tanzania.

Several studies have been conducted on mechanical properties of wood of Eucalypt clones and other *Eucalyptus* species. For example, Lima *et al.* (1999), Acosta *et al.* (2008) and Hein and Lima (2012) evaluated strength properties of *E. grandis* and Eucalypt clones in Brazil and found low Modulus of Elasticity (MOE), Modulus of Rupture (MOR) and compression strength (CS) compared to values needed for structural applications. Souza *et al*. (2009), Nazmul *et al.* (2012) and Bal and Bektaş (2014) studied the mechanical properties of *E. camaldulensis, E. urophylla* and *E. grandis* in India and Turkey and reported that the wood of the species had better mechanical properties which were within the specified range needed for plywood and furniture production. In Kenya, few studies have investigated the mechanical properties of wood of Eucalypt clones. For example, Muga *et al.* (2009) reported that wood from Eucalypt clones had the same or higher MOE, MOR and CS as their parents. However, no study has been conducted on mechanical properties of wood of Eucalypt clones growing in Tanzania. Therefore, knowledge of the wood properties is required to define efficient utilization of wood in different applications (Lima *et al.,* 2000).

1.2.2 Justification of the study

This study provides information on the best clones which performed well in the studied sites to be grown in areas with climatic conditions similar to the sites where they were tested. The information generated on the amount of water used by Eucalypt clones extends the knowledge on and adoption of Eucalypt clones by various stakeholders in Tanzania. In addition, information generated on wood properties will be used as a basis of making recommendations which will lead to efficient utilization of wood of Eucalypt clones. Furthermore, this study generated information which is of importance to policy and decision makers, tree farmers, public and private sector plantation managers, research and training institutions and Non Governmental Organizations (NGOs) in Tanzania. The information generated will be used as a basis for making decisions on planting Eucalypts in Tanzania.

1.3 Research Objective

1.3.1 Overall objective

To assess the growth performance, water use and wood properties of Eucalypt clones grown at Lushoto, Kibaha, Kwamarukanga and Tabora sites.

1.3.2 Specific objectives

i) To assess the survival, growth and productivity of Eucalypt clones growing at Lushoto, Kibaha, Kwamarukanga and Tabora sites.

ii) To investigate the amount of water used by Eucalypt clones growing at Kongowe, Kibaha site.

iii) To determine physical and mechanical properties of wood of Eucalypt clones growing at Lushoto, Kibaha, Kwamarukanga and Tabora sites.

1.4 Research Hypothesis

Null hypothesis: There are no significant effects on the growth performance, water use and wood properties of Eucalypt clones within sites.

Alternative hypothesis: There are significant effect on the growth performance, water use and wood properties of Eucalypt clones within sites.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Eucalypts Global Informantions

Eucalyptus is one of the leading forest species domesticated throughout the world (Srivastava *et al.,* 2003). No other tree species except *Eucalyptus* has ever been so widely propagated throughout the world since it contains a remarkably wide range of tree species in regard to adaptation to site, types of management systems and multipurpose uses (Srivastava *et al.,* 2003; Dos Santos *et al.,* 2004). Eucalypt plantations can exhibit some of the fastest growth rates of any plantation species but the genus also includes species that can maintain acceptable growth rates under harsh conditions (Beadle and Sands, 2004), marshy and swampy sites and under a variety of soils including fertile loamy soils, infertile sands and heavy clays (Oballa *et al.,* 2009). These fast growing species can be grown under a range of different climates for products that include pulp and paper, charcoal, fuelwood, and solid wood products such as poles, furniture and timber for construction (Albaugh *et al.,* 2013).

Eucalyptus species are found in over 90 countries (Doughty, 2000). Brazil, China, India and South Africa (Davidson, 1995; Stape *et al.*, 2001; Stape, 2002; Liu and Li, 2010; ICFRE, 2010; Zegeye, 2010) are the major *Eucalyptus* growing countries. In Africa, South Africa has the largest area under Eucalypt plantations of about half a million ha (Teketay, 2003). In Eastern Africa, the genus *Eucalyptus* was introduced in the late 19th and early 20th centuries and by early 2002, the area under Eucalypts in Ethiopia, Rwanda, Uganda, Kenya, Burundi and Sudan had reached 742,765 ha (Getahum, 2002; Oballa *et al.,* 2005). Currently, in Kenya, *Eucalyptus* species account for about 10% of tree plantation area (KFMP, 1994; KFS, 2009). Table 1 presents the area coverage of Eucalypt plantations in various countries in the world.

Table 1: Area coverage of *Eucalyptus* plantations in some countries in the world

Country	Area under *Eucalyptus* plantations (ha)
Brazil	3,700,000
India	2,500,000
China	1,700,000
Portugal	550,000
South Africa	477,000
Spain	396,000
Ethiopia	250,000
Morocco	200,000
Chile	170,000
Australia	125,000
Thailand	100,000
Kenya	100,000
Total	10,268,000

Source: Turnbull (1999); KFS (2009); Zegeye (2010); Liu and Li (2010); ICFRE (2010)

In Tanzania, Eucalypts were introduced in early 1890s with the aim of supplementing wood supplies from natural forests (Nshubemuki *et al.,* 2001). The planted species include *E. saligna*, *E. grandis, E. camaldulensis, E. globulus, E. viminalis, E. citriodora, E. regnans* and *E. microtheca* (Munishi, 2007). Eucalypts are among the major species grown under small holder forestry and are a major source of transmission poles, building material, industrial wood, poles, timber, fuelwood, bee forage, essential oils and many environmental services such as windbreaks, erosion control, buffer to natural forests, flood control and climate change mitigation (Munishi, 2007; Oballa *et al.,* 2009).

2.2 Eucalypt Clones

Mondi Forests in South Africa started an intensive hybrid breeding programme in 1968 with *E. grandis* and other species for planting in marginal areas and increasing productivity from existing plantations (Denison, 1998). They came up with a number of hybrid clones for subtropical and temperate areas. The most common hybrid combinations for subtropical areas are *Eucalyptus grandis* crossed with *E. camaldulensis* (GC), *E. grandis* crossed with *E. urophylla* (GU), and *E. grandis* crossed with *E. tereticornis* (GT) (Denison and Kietzka, 1993). For temperate areas, the hybrids produced are *E. grandis* x *E. nitens* (GN) and *E. grandis* x *E. macarthurii* (GM) (Denison and Kietzka, 1993). These hybrids outperform the pure species on marginal sites and are consistently more resistant to diseases, pests, cold, heat and drought and have more homogenous wood density (Denison and Kietzka, 1993).

In late 2003, *Eucalyptus* hybrids were introduced to Tanzania from Mondi South Africa (Msangi *et al.*, 2009) with the aim of transferring clonal tree propagation technologies as a means to hasten large-scale improvement of plantations particularly of Eucalypts and hence contribute to improvement of living standards of rural communities. The most popular hybrids introduced in Tanzania are GC, GU and GT (Denison and Kietzka, 1993; Msangi *et al.,* 2009; Oballa *et al.,* 2009). These clones combine desired traits for the crossed species. *E. grandis x E. camaldulensis* (GC) combines good growth and drought tolerance, *E. grandis x E. urophylla* (GU) combines good growth and disease resistance while *E. grandis x E. tereticornis* (GT) combines good growth and rooting ability (Cupertino *et al.,* 2011). The bole of Eucalypt clones is straight for 2/3rds to 3/4 the height of the tree (Eldridge *et al.,* 1993). The GC hybrids are more suited for growing in areas with medium agricultural potential, receiving annual rainfall of above 750 mm and at an elevation of less than 1700 m a.s.l (Oballa *et al.,* 2009). The GCs are not suitable for growing in semi-arid areas where *E. camaldulensis* does best or above 1700 m a.s.l. where *E. grandis* grows best. In high rainfall areas with amounts over 1200 mm a year, the growth rate of GCs is lower than that of the widely grown *E. grandis* (Wamalwa *et al.*, 2007).

2.3 Growth Rate of Eucalypts from Seed and Clones

Eucalyptus species are commercially grown worldwide by small farmers and large conglomerates for industrial wood supply (Myburg *et al.,* 2006). The growth rate of Eucalypts depends on different management factors including spacing, site conditions, amount of rainfall, silviculture and genetics, although they are capable of growing successfully in all ecological conditions. If the planting sites have good conditions for nutrient and water, Eucalypts provide output from third or fourth year depending on the management objectives (Getahun, 2002; Kebebew and Ayele, 2010).

The growth rate and productivity of *Eucalyptus* species may vary from country to country and even within a country and from one stand to another (Eldridge *et al.,* 1993; Marcar and Crawford, 2004; Boland *et al.,* 2006). Intensive silvicultural practices and traditional genetic improvement have both contributed to improve the productivity (Gion *et al.,* 2011). The variations in MAI with age generated from different parts of the world are shown in Table 2.

Table 2: Growth rates of Eucalypts plantations in different parts of the world

Species	Location	Age	MAI (m^3 ha^{-1} yr^{-1})	Forest type	References
Eucalyptus grandis	Brazil	10	33-70	Plantation	Turnbill (1999)
E. grandis	Costa Rica	6.5	49-112	Plantation - Fertilizer and spacing	Vásquez and Ugalde (1995[a])
Eucalyptus species	Brazil	6 – 8	100	Plantation	Ugalde and Pérez (2001)
Eucalyptus species	Papua New Guinea	3	80 – 90	Plantation	Eldridge *et al*. (1993)
E. grandis	New South Wales	3	25	Plantation irrigated with effluent	Myers *et al.* (1996)
E. urophylla	Brazil	10	33-70	Plantation	Turnbill (1999)
Eucalyptus species	Burundi	8	1-2	Plantation	Brown *et al.* (1997)
E. camaldulensis	Tanzania	*	15-30	Plantation	Ugalde and Pérez (2001)
E. grandis	Tanzania	*	15-50	Plantation	Ugalde and Pérez (2001)
E. saligna	Tanzania	*	10-55	Plantation	Ugalde and Pérez (2001)
E. globules	Tanzania	*	10-40	Plantation	Ugalde and Pérez (2001)
Eucalyptus species	Congo	7	30	Plantation	Brown *et al.* (1997)
E. globulus, E. nitens	Chile	10	10-40	Plantation	Pinilla *et al*. (1999) in Ugalde and Pérez (2001)
Eucalyptus species	Rwanda	8	8.5	Plantation	Brown *et al.* (1997)
Eucalyptus species	South Africa	8-10	18-20	Plantation	Brown *et al.* (1997)
E. grandis and its hybrid	South Africa	*	15-55	Plantation	Du Toit *et al.* (1998)
Eucalypts plantation	India	*	5-10	Plantation in Moonsoonal Tropics	Sankaran (1998)
E. urophylla	Congo	5	40	Plantation	Eldridge *et al*. (1993)
E. urophylla	Cameroon	8	30-83	Plantation	Eldridge *et al*. (1993)
E. camaldulensis	Argentina	7-15	20-25	Plantation	Lamprecht (1990)
E. camaldulensis	Israel	7-15	30	Plantation	Lamprecht (1990)
E. camaldulensis	Turkey	7-15	17-20	Plantation	Lamprecht (1990)
E. camaldulensis	Morocco	7-15	3-11	Plantation	Lamprecht (1990)
E. camaldulensis	Portugal	7-15	2-10	Plantation	Lamprecht (1990)
E. camaldulensis	Italy	7-15	6-7	Plantation	Lamprecht (1990)
Eucalyptus clones	India	6	28-54	Plantation	Kulkarni (2002)

a. Experiment with fertilizer and spacing, * Age not available

2.4 Growth Rates of Other Tree Species

There has been very diverse productivity of planted forests ranging from good performance of over 30 m^3 ha^{-1} yr^{-1} to poor performances of 1-2 m^3 ha^{-1} yr^{-1} (Tiarks *et al.,* 1998; FAO, 2003a; FAO, 2003b; Chamshama and Nwonwu, 2004). But generally, 10-20 m^3 ha^{-1} yr^{-1} is regarded as an achievable yield for different species over large areas

(Ugalde and Pérez, 2001; Du Toit *et al.,* 1998). This large variation in productivity is due to a number of factors such as species/provenance selection, genetic improvement, species-site matching and cultural practices (Vichnevetskaia, 1997; FAO, 2001a, b). The productivity of plantations needs to be high and sustainable in order to be economically viable because of the large investment made (Tiarks *et al.,* 1998). Table 3 presents growth rates of different species in forest plantations in different parts of the world.

Table 3: Annual volume increment of different species from various parts of the world

Species	Location	Age	MAI (m^3 ha^{-1} yr^{-1})	Forest type	References
Casuarina equisetifolia	Australia	10	15	Plantation	Pinyopusarerk and House (1993)
Dalbergia sissoo		10	9-15	Plantation	Ugalde and Pérez (2001)
Pines	Brazil	16-25	15-25	Plantation**	Brown *et al.* (1997)
Pines	Venezuela	10-20	10	Plantation**	Brown *et al.* (1997)
Pinus patula	Tanzania	25-30	20-25	Plantation	Chamshama (2011)
C. lusitanica	Tanzania	25-30	12-25	Plantation	Chamshama (2011)
Pinus caribeae	Tanzania	*	20-50	Plantation	Ugalde and Pérez (2001)
Pines	Chile	20-30	24	Plantation**	Brown *et al.* (1997)
Pines	Malawi	20-25	17	Plantation**	Brown *et al.* (1997)
Pines	Madagascar	15-18	6-10	Plantation**	Brown *et al.* (1997)
Pines	Mozambique	18-25	11	Plantation**	Brown *et al.* (1997)
Acacia mearnsii	Indonesia	7-10	10-25	Plantation	Du Toit *et al.* (1998)
Acacia mearnsii	South Africa	7-10	12	Plantation	Du Toit *et al.* (1998)
Cedrelinga	Ecuador	15	23	Plantation ***	Alder (1999)
Jacaranda	Ecuador	15	16	Plantation ***	Alder (1999)
T. superba	Tanzania	*	10-14	Plantation	Wadsworth (1997)
Cordia	Ecuador	10	8	Plantation***	Alder (1999)

*Age not available; ** Plantation of tropical forest; *** Plantation of lowland tropics

2.5 Eucalypts and Water Use

2.5.1 Water use

Water use by plantations has received prominent attention in many circles in recent years (Farley *et al.,* 2005; Jackson *et al.,* 2005; Brown *et al.,* 2007; Dijk and Keenan, 2007; Dijk *et al.,* 2007; Dye and Versfeld, 2007) but the evidence presented remains equivocal.

Apparently, planting of Eucalypt in Ethiopia and elsewhere has been faced with controversies based on ecological and socio-economic arguments (FAO, 1988; Jagger and Pender, 2000). The major argument has been that Eucalypts remove too much water from underground reserves and inhibit the growth of other vegetation (Calder *et al.,* 1992; Olbrich *et al.,* 1993; Kallarackal and Somen, 1997; Jagger and Pender, 2000; Soares and Almeida, 2001; Chamshama and Nwonwu, 2004; Mbinga, 2009; KFS, 2009; Albaugh *et al.,* 2013).

In Kenya, concerns have been raised about the high water consumption of Eucalypt trees, which in 2009 led to the country's Environment Minister ordering uprooting of Eucalypt trees from wetlands and banning their planting along rivers and watersheds (WRM, 2010). According to Davidson (1989), many of the criticisms are unfair, biased, nationalistic or emotional and could apply equally to other exotic trees planted in many countries as they are not peculiar to Eucalypts. Some Eucalypts can grow even in sites considered too dry for many other tree species (Myers *et al.,* 1996; Beadle and Sands, 2004). The relationships between forests and water resources are complex and will vary with topography, soil type, local climate and the type of tree involved in a variety of other factors which exert their own particular influence (Chamshama and Nwonwu, 2004).

Eucalypts impacts and responses at different sites are complex and may require substantial research and adequate information on water use before conclusive arguments can be made (Munishi, 2007). The controversies surrounding planting of Eucalypts in Tanzania, especially as relates to water use and effects on water resources, still require a more intensive investigation before an informed advice is offered given the variety of *Eucalyptus* species to be planted in the different ecological regions of the country (Munishi, 2007). High rates of productivity of Eucalypts are often associated with high rates of water use leading to concerns about reductions in yield from water supply catchments in Australia or where Eucalypts forests have replaced native vegetation of low stature in South Africa (Dye, 1996) and Southern India (Calder, 1992). For this reason, nearly all commercial plantation programmes in South America have strict legal limits on how close to a water source they can plant trees (Lima, 2011). The severity of problems associated with water availability appears to be greater in areas where the plantations are large in size and cover most of the catchment area or in places with seasonal rainfall.

In countries with large Eucalypts plantations, studies have been carried out on water use by various tree species including pines (Oballa *et al.,* 2009). Assessments have also been conducted on the effects of land use change from grassland or indigenous forests to plantations of fast growing species of Pines and Eucalypts. Results showed that in high rainfall areas, replacement of indigenous bamboo forest in water catchment with plantations of Eucalypts, pine and tea did not result in any long-term reduction in water from the catchments (Oballa *et al.,* 2009). In dry sites, Eucalypts adopt various mechanisms for avoiding drought including dynamic changes in leaf area index, near vertical arrangement of leaves, high stomata sensitivity to air saturation deficit, deep rooting ability and osmotic manipulation to maintain turgor in leaves (Whitehead and Beadle, 2004).

According to Kilimo Trust (2011), all trees consume water as they grow but the criticism that Eucalypts use excessive amounts of water causes the most concern because of its potential of reducing water resources in regions that already have water shortage. Fast growing trees consume more water than slow growing trees (Kilimo Trust, 2011; Chamshama and Nwonwu, 2004), thus reducing the water available to those living downstream. However, plantations with a growth rate similar to a natural forest will not use more water than Eucalypts. Neither will Eucalypts use more water than any other pioneer tree species growing as fast as they do e.g. some Acacias (Chamshama and Nwonwu, 2004). However, like all other plants, Eucalypts will also adjust the amount of water they consume in line with the water available. When the soil is wet and the water table is near the surface, the trees will take more water but when the soil dries, the trees take less water (Kilimo Trust, 2011).

High rates of productivity of Eucalypts are often associated with high rates of water use leading to concerns about reductions in yield from water supply catchments in Australia (Langford and O'Shaughnessy, 1980; Ruprecht and Stoneman, 1993), or where Eucalypt forests have replaced native vegetation of low stature in South Africa (Dye, 1996) and southern India (Calder, 1992). Calder *et al*. (1992) reported that roots of Eucalypts penetrate into deeper soil layers and are able to extract water from reservoirs additional to that available from rainfall. The additional access to water was found to support increased growth compared to other tree species within the site.

Several studies have captured some of the concerns on Eucalypts and their effects on stream flows. Robertson (2005) in South Africa observed that when the Eucalypts and other exotic species were cleared from the river systems, the flow of the river was restored to normal within a decade, indicating that the ground water accumulates and springs up. Scott and Welch (1996) reported similar experiences in an afforestation scheme with *E. grandis* in one site and *Pinus patula* in another site in South Africa. In both cases, the species dried the stream after some years. After clear felling, the stream flow returned to normal within a period of 5 years. It is important to note that such large-scale clearance can have negative repercussions leading to dry land salinity as observed by Morgan and Barton (2008) when done with the hope that indigenous species will automatically colonize without silvicultural treatment. Munishi (2007), going by the observations in Mbeya, Tanzania, cautions that the approach of large scale clearance is not advised since the sudden drastic removal of vegetation over large areas on steep slopes invariably leads to increased soil erosion, landslides, and silting of waterways and water bodies, with increased floods on farmlands and other habitats.

2.5.2 Water use by Eucalypts compared with other tree species

Regarding the claims on high water use by Eucalypts, one must take account not only the absolute volume of water consumed, but also the amount of biomass and other goods and services produced per unit of water consumed (Jagger and Pender, 2000). In India, water use by Eucalypts hybrids were compared to that of species of other genera, including fast growing *Albizia* species, *Acacia* species and *Dalbergia sissoo* (Tiwari, 1992). The study showed that Eucalypts consumed 0.48 litres of water to produce a gramme of biomass compared to *Albizzia lebbek, Acacia auriculiformis* and *Dalbergia sissoo* which had higher water use to produce same amount of biomass (Tiwari, 1992) (Table 4).

Table 4: Water consumption of Eucalypts compared with other tree species

Species	Water consumed (litres/yr)	Biomass Produced				Total Biomass Produced per litre of Water (g /Litre)	Water Consumed per g of biomass (litres /g)
		Shoots	Roots (g / yr)	Leaves	Total		
Acacia auriculiformis	1231.50	1023.5	361.6	327.9	1713.0	1.39	0.72
Albizzia lebbek	1283.90	1132.4	1085.6	136.8	2354.8	1.83	0.55
Dalbergia sissoo	1534.05	1129.3	775.5	99.77	2004.5	1.31	0.77
Eucalyptus hybrid	2526.35	2519.0	2094.3	594.9	5209.0	2.06	0.48

Source: Tiwari (1992)

Chaturvedi *et al.* (1988) reported that of ten species tested for water consumption, *E. tereticornis* was found to be the most efficient in biomass production per litre of water consumed. Studies in Australia have shown that Eucalypts use water conservatively (as opposed to coniferous forests) and that water use is generally consistent with stands of other tree species (Tiwari and Mathur, 1993). One well quoted research report (Davidson, 1989) showed that for the same amount of water, *E. saligna* and *E. grandis* could produce 46 m^3 of wood ha^{-1} $year^{-1}$ whereas conifers produced only 16.4 m^3 of wood ha^{-1} $year^{-1}$.

Most *Eucalyptus* species need on average 785 litres of water per kilogramme of biomass produced (Davidson, 1993). This is in contrast to other crops which use much greater amounts of water to produce the same amount of biomass. Cotton, coffee, and bananas for example, require 3,200 L kg^{-1} of biomass while maize requires 1000 L kg^{-1} (Table 5) (Davidson, 1989).

Table 5: Water use per kilogramme biomass produced by different crops

Species	Litres of water /kg biomass produced
Cotton/coffee/banana	3200
Sunflower	2400
Paddy Rice	2000
Field pea	2000
Horse Bean	1714
Cow Pea	1667
Soy Beans	1430
Potato	1000
Sorghum	1000
Eucalypts	785
Finger Millet	592

Source: Davidson (1993)

2.5.3 Factors influencing tree water use

Water use by trees is influenced by several environmental variables, including vapour pressure deficit, net radiation, wind speed and temperature (Zotz *et al.,* 1998). It is also influenced by the availability of soil water within the rooting zone (David *et al.,* 1997). Morris *et al.* (2004) and Kilimo Trust (2011) reported that the rate of water use by

Eucalypts is highly variable, responding to weather condition, species and hybrid, soil type and depth, vegetative cover, tree growth stage, wood density and tree rooting depth. Other factors include season, soil water availability, age and diameter of the trees, leaf area and tree density (Dye *et al*., 1995). The impact of these variables on the amount of water transpired depends on tree leaf area and the stomata behaviour of the species (White *et al.,* 1999).

2.6 Eucalypt Wood Properties

2.6.1 Physical properties

2.6.1.1 Wood density

Wood density is the mass of oven-dry material per unit of volume and is expressed in kilogrammes per cubic metre or gramme per cubic centimetre (Williamson and Wiemann, 2010). It is affected by the proportions of cell wall materials of the wood, cell diameter and the chemical content of the wood and is hence dependent on the ratio of cell wall thickness to cell diameter (Hashemi and Kord, 2011). Dinwoodie (1981) reported that the thicker the cell wall, the higher the density and hence, the stronger the wood. Wood density may vary between trees of the same species due to genetics, wood anatomy such as fiber diameter, wall thickness and proportion of non-fibrous cell types. Other causes of variation include chemicals such as ash and extractives content, silvicultural effects and ecological differences as well as within a tree, i.e., age-related longitudinal and radial variation (Quilhó *et al.,* 2006). Studies carried out by Malan (1988) revealed significant genetic variations of wood density, proportional volume of the various tissue types, vessel frequency, fibre length and growth stresses. Wood density is an important property for wood utilization and conversion (Zobel and van Buijtenan, 1989). Haygreen and Bowyer (1996) reported that the strength of wood is usually closely correlated to density and it is possible to estimate wood strength based on density without detailed knowledge of the species. Miranda *et al.* (2001) reported that growth rate of trees is positively correlated to wood density in *E. globulus*. Tree diameter measured at breast height (Dbh) is an economically important trait as it separates logs into different production systems with disparate cost and revenue structures (Blackburn *et al.,* 2011). For higher density species, greater Dbh equates to greater recovery of higher-value select and standard grade sawn boards as a proportion of log volume (Blackburn *et al.,* 2011).

According to Malan (1995) and Githiomi and Kariuki (2010), high-density mature wood of Eucalypts begins to form at about 5 to 8 years. Denison and Keitzka (1993 a), de Assis (2000) and Verryin (2000) reported that it was common for wood properties of various Eucalypt clones to be intermediate between their parents but have superior growth to both parents. Varied wood basic densities have been reported by various authors. Tables 6 and 7 present wood basic densities of Eucalypt clones and Eucalypts from seed respectively. According to Acosta *et al.* (2008), the basic density of Eucalypts varies from a minimum of 319 kg m^{-3} to a maximum of 731 kg m^{-3} while Sansígolo and Ramos (2011) reported that basic density in Eucalypts wood can vary from 300 to 800 kg m^{-3}. Others, for example ITTO (2006) reported that wood with an air dried-density smaller than 560 kg m^{-3} is considered to be a small-density species, that between 560 and 750 kg m^{-3} is considered to be a medium-density, that between 750 kg m^{-3} and 950 kg m^{-3} is considered to be a large-density species, and higher than 950 kg m^{-3} is considered to be an extra-large density species. Basing on this classification, *E. urophylla x E. grandis* (clone) wood has a medium density.

Table 6: Values of basic density found by various authors for Eucalypt clones

Species	Age (years)	Basic density (kgm^{-3})	Location	References
Eucalyptus clones	7.5	530 – 590	Brazil	Pereira *et al.* (2012)
Eucalyptus pellita	5	560	Brazil	Oliveira *et al.* (2010)
Eucalyptus clones	6.8	486 – 495	Brazil	Quilhó *et al.* (2006)
Eucalyptus hybrid	5.6	460 – 491	Brazil	Gominho *et al.* (2001)
Eucalyptus clones	8	420 – 560	Brazil	Lima *et al.* (2000)
GC and GU clones	11	627 – 664	Uganda	Turinawe *et al.* (2014)
Eucalyptus clones	12.9	530 – 658	Argetina	Acosta *et al.* (2008)
Eucalyptus clones	7.3	545 – 563	South Africa	Zbonak *et al.* (2007)
E. saligna clones	<3.5	319 – 517	Brazil	Lima (1995)
Eucalyptus clones	5 – 6	552 – 560	Kenya	Muga *et al.* (2009)
Eucalyptus clones	7	500 – 550	Brazil	Santos *et al.* (2011)
Eucalyptus hybrids	9	447 – 591	Argetina	Acosta *et al.* (2008)
Eucalyptus clones	6	508 – 594	Argetina	Acosta *et al.* (2008)
Eucalyptus clones	8	477 – 584	Argetina	Acosta *et al.* (2008)
Eucalyptus clones	7.5 – 13	449 – 563	Argetina	Acosta *et al.* (2008)
Eucalyptus clones	13 – 17	544 – 731	Argetina	Acosta *et al.* (2008)
E. grandis clones	9	520 – 698	*	Castro and Paganini (2003)

Table 7: Wood basic density of Eucalyptus from seed

Species	Age (Years)	Basic density kgm^{-3}	Location	References
Eucalyptus grandis	3	495	India	Bhat *et al.* (1990)
Eucalyptus grandis	5	420	India	Bhat *et al.* (1990)
Eucalyptus grandis	7	485 – 490	India	Carvalho and Nahuz (2001)
Eucalyptus grandis	9	497	India	Bhat *et al.* (1990)
Eucalyptus globulus	7	442 – 450	*	Miranda *et al.* (2001)
Eucalyptus saligna	4	340 – 520	Hawaii	King (1980)
Eucalyptus saligna	15	349 – 496	Hawaii	DeBell *et al.*(2001)
Eucalyptus grandis	*	450 – 600	Morocco	Loulid *et al.*(2012)
Eucalyptus from seed	6.8	397 – 464	Brazil	Quilhó *et al.*(2006)
E. grandis	18	580	Lavras	Albino *et al.*(2010)
Eucalyptus grandis	10	517	Kenya	Githioni and Kariuki (2010)
E. camaldulensis	5 – 6	540	Kenya	Muga *et al.* (2009)
E. tereticornis	5 – 6	540	Kenya	Muga *et al.* (2009)
E. grandis	5 – 6	450	Kenya	Muga *et al.* (2009)

*Data not available

2.6.1.2 Fibre length

Fibre length is one of the quality parameters in pulp and paper production. It plays a significant role in paper making as it influences the strength especially when short-fibred Eucalypts are used as raw material (FAO, 1970). Fibre attributes have been related to different wood quality indices such as felting coefficient where higher values are associated with better resistance of paper and is also used by the pulping industry as indicator of wood quality for different industrial processes and final paper products.

The index has a positive influence on the physical and mechanical properties of wood-based products such as paper, paper board, insulation board, medium-density fiberboard, particleboard, hardboard, and wood fibre polymer composites (Panshin and De Zeeuw, 1980).

According to Quilhó *et al.* (2006), the average fibre length of Eucalypt clones in Brazil ranged from 1.009 to 1.108 mm and 0.824 to 1.035 mm from seeds at 6.8 years. Grzeskowiak *et al.* (2000) and Carvalho and Nahuz (2001) reported fibre length ranging from 0.81 to 1.08 mm for GU hybrid trees at 7 years. The fibre length values of the parent species are 0.812 mm, 0.995 mm, 1.086 mm and 1.147 mm for respectively 3, 5, 7 and 9 year old *E. grandis* (Bhat *et al.,* 1990) and 1.17 mm for 35 years old trees (Malan, 1995). The GU hybrid shows fibre lengths similar to other Eucalypt species used for pulping, *i.e.* 0.85 mm and 0.94 mm in 4.5 year old *E. tereticornis* (Rao *et al.,* 2002), 0.82 mm to 0.93 mm in 7 year old GC (Grzeskowiak *et al.,* 2000), as well as 0.89 mm to 0.93 mm in 9 year old, and 0.87 mm to 1.04 mm in 15 year old *E. globulus*, the important species for pulp production (Jorge *et al.,* 2000; Miranda *et al.,* 2001).

Fibre length, diameter and wall thickness increase rapidly with increasing distance from the pith, leveling off after about 8 to 15 years (Malan and Gerischer, 1987; Bhat *et al.,* 1990). Height of tree has little effect on fibre length, while fibre diameter increases with height in a tree to about mid-height followed by a decrease higher up (Taylor, 1973 a, b; Bhat *et al.,* 1990). Taylor (1973b) in South Africa found significant difference in fibre length between-tree. On the other hand, Bhat *et al.* (1990) observed no significant difference in fibre length between trees. Various methods can be used for fibre length determination. Bowyer (2003) reported that fibres were macerated using a mixture of 30% hydrogen peroxide: glacial acetic acid at a ratio of 1:1 at 45^0C. Macerated fibres are thoroughly mixed and are spread on a glass slide, and 100 unbroken fibres were selected for measurement.

2.6.2 Mechanical properties

2.6.2.1 Static bending

Static bending is a measure of the strength of a material as a beam. It measures the effect of compression, shear and tensile stresses operating together (Desch and Dinwoodie, 1981). Static bending test involve modulus of rupture (MOR), modulus of elasticity (MOE), work to maximum load and total work. MOR is the equivalent stress in the extreme fibres of the specimen at the point of failure. MOE is a measure of stiffness of an elastic material. It is used to describe the elastic properties of objects like wires, rods or columns when they are stretched or compressed (Desch and Dinwoodie, 1981). Elasticity is defined as the property which enables a loaded material to recover its original form after the load is removed. If the load is greater than a certain value, the material will display a plastic deformity or even failure. The elasticity and density properties are fundamental in determining the quality of wood (Ilic, 2003).

There is a general trend and pattern of variations in MOR, MOE and compression strength (CS) tangential to grain within and between trees of the same and different age classes (Izekor and Fuwape, 2010). The properties decrease from the tree base to the top and increase from the pith outward to the bark and increase with increase in age. The trend of increase in MOR values from inner wood to outer wood may be associated with variations in some morphological factors such as fibre length, wall thickness and fibre diameter while increasing MOE values with increasing age of the tree are attributed to the increment of growth rings and the addition of more mature wood as well as the increased age of the cambium as the tree grows in girth. Therefore, the effect of age is the most important source of variation in MOR, MOE and CS of plantation grown Eucalypts.

Olufemi and Malami (2011) reported that MOR in bending of wood of *E. camaldulensis* growing in North western Nigeria ranged from 88.8 to 157.66 N mm^{-2} with mean value of 133.33 N mm^{-2}. It is reported that the locations show significant ($p<0.05$) difference in static bending. MOE in bending of *E. camaldulensis* ranged from 9048.49 to 19388.71 N mm^{-2}, with overall mean value across the northwest ecological zone of Nigeria of 15319.89 N mm^{-2}. Bal and Bektas (2013) reported that MOE for *E. grandis* in Turkey was 10074 N mm^{-2} for sapwood and 8412 N mm^{-2} for heartwood while MOR was 100 N mm^{-2} for sapwood and 84 N mm^{-2} for heartwood. Table 8 presents values of wood mechanical properties for Eucalypts reported by various authors.

Table 8: Values of mechanical properties of Eucalypts wood reported by various authors

Genetic material	Age (Years)	Location	Mechanical characteristics CS	MOR	MOE
E. hybrids clones	9	Brazil	49-61	89-116	15491-19947
GC clones	5-6	Kenya	*	88-129	7866-15080
Eucalyptus genotypes	13-17	Brazil	*	97-143	13924- 24015
Eucalyptus clones	5.5-10.5	Brazil	40-52	78-108	8768-19670
Eucalyptus clones	8	Brazil	45-57	91-115	6139-7576
E. camaldulensis	10	Nigeria	*	89-154	15319.89
E. clones and one progeny	12.9	Brazil	51-62	99-111	6932-7914
E. camaldulensis	20	Nigeria	51.85	*	*

Note: CS = compression strength parallel to the grain; MOR = modulus of rupture in static bending N mm^{-2}; MOEb = modulus of elasticity in static bending, N mm^{-2}; * Data not available.
Source: Acosta *et al.* (2008); Olufemi and Malami (2011); Malami and Olufemi (2013).

2.6.2.2 Cleavage strength

Cleavage strength is an important property in practical use of wood as fuel, as it determines the ease of splitting (Ishengoma and Nagoda, 1991). FPL (2010) reported that straight grained timber splits more readily radially than tangentially, and more readily when dry than when green, but timbers with markedly interlocked grain split more readily tangentially and are often extremely difficult to split radially. The same author also pointed out that the readiness of a timber to split, which cleavage denotes has a practical application in certain circumstances. For instance in firewood and material for the manufacture of tight barrels, charcoal and hand-split shingles, high cleavage is a very desirable property. Turinawe *et al.* (2014) reported cleavage strength ranging from 18 to 20 Nmm^{-2} for Eucalypt clones and 16 to 33 Nmm^{-2} for *E. camaldulensis* in Uganda. Similarly, Moya and Muñoz (2010) reported higher cleavage strength in the tangential direction than in the radial direction. Ismaili *et al.* (2013) documented that, cleavage strength in the tangential direction was higher than in the radial direction for both green and air-dry wood in Malaysia. Wallis (1970) found that lower values of cleavage in the radial direction were due to the relationship between air-dry density and the cleavage strength of timber along the fibres. This test is normally carried out in both radial and tangential surfaces to give an average cleavage strength value (Ishengoma and Nagoda, 1991).

2.6.2.3 Compression strength

Compression strength is the ability of a wood member to resist the impact of forces or loads acting along the same axis and trying to shorten a dimension or reduce the volume of the wood. Wood in service is constantly interacting with so many forces, of which compressive forces are the most prominent. Results from this test are important for predicting wood used in columns and structural materials. According to Akpan (2006), high strength in longitudinal compression is required in timber used as columns, props and chair legs. For some selected end uses such as railway sleepers, rollers, wedges, bearing blocks and bolted timbers, resistance to crushing is an important property. Timbers with high density have high compression strength across the grain

(Akpan, 2006). Studies have revealed that wood is weaker in compression perpendicular to the grain than it is in compression parallel to the grain (Stalnaker and Harris, 1989).

Malami and Olufemi (2013) have reported compression strength parallel to the grain of *E. camaldulensis* across the north-western zone Nigeria ranged from 37.44 to 78.55 N mm^{-2} with the overall mean value of 61.85 N mm^2. In comparison with other *Eucalyptus* species, it can be said that *E. camaldulensis* has higher compression strength than its counterparts like 39.43 N mm^{-2} for *E. saligna*, 28.57 N mm^{-2} for *E. robusta*, 45.79 N mm^{-2} for *E. grandis* and 55.29 N mm^{-2} for *E. butryoides* (Malami and Olufemi, 2013). It is however lower in this respect than *E. cloeziana* at 75 N mm^{-2} (FPR, 1969). For *E. grandis*, compression strength of 60 and 52 N mm^{-2} was reported for sapwood and heartwood respectively in Turkey (Bal and Bektas, 2013). Lima *et al.* (2000) reported compression strength ranging from 49 to 65 N mm^{-2} for 8 year old Eucalypt clones in Brazil.

2.6.2.4 Shear strength

Shear strength is the ability to resist internal slipping of one part upon another along the grain. It is the measure of the resistance of the timber to break apart when subjected to sliding forces (Ishengoma and Nagoda, 1991). Results from shear tests are important for predicting the behaviour of wood when subjected to joining; hence, lower shear strength presents design of joints problems (Walker, 1993).

Acosta *et al.* (2007) found shear strengths of wood of GT hybrid in Argentina of 10.7 N mm^{-2} and 11.3 N mm^{-2} on the radial and tangential surfaces respectively. Dos Santos *et al.* (2004) in Brazil reported shear strength of 12.61 N mm^{-2} for wood of *E. grandis* of 8 year old. Bal and Bektas (2013) reported shear strength parallel to grain for *E. grandis* of

10 N mm^{-2} for sapwood and 8 N mm^{-2} for heartwood in Turkey. In Malaysia, shear parallel to the grain for *Engkabang jantong* was 6.41 N mm^{-2} and 8.62 N mm^{-2} (Ismaili *et al.,* 2013).

2.6.2.5 Factors affecting strength properties

2.6.2.5.1 Natural characteristics related to wood structure

Specific gravity

Specific gravity affects mechanical properties because the substance of which wood is composed is actually heavier than water; its specific gravity is about 1.5 regardless of wood species. In spite of this, the dry wood of most species floats in water and it is thus evident that part of the volume of a piece of wood is occupied by cell cavities and pores. Variations in the size of these openings and in the thickness of the cell walls cause some species to have more wood substance per unit volume than other species and therefore higher specific gravity. Thus, specific gravity is an excellent index of the amount of wood substance contained in a piece of wood and it is a good predictor of mechanical properties as long as the wood is clear, straight grained, and free from defects (FPL, 2010).

Knots

A knot is that portion of a branch that has become incorporated in the bole of a tree. The influence of a knot on the mechanical properties of a wood member is due to the interruption of continuity and change in the direction of wood fibers associated with the knot. The influence of a knot on the performance of lumber depends upon the size, location and shape of the knot as well as attendant grain deviation around the knot and the type of stress to which the wooden member is subjected. Knots have a much greater effect on strength in axial tension than in axial compression. Knots decrease most mechanical properties because the clear wood is displaced by knots, the fibers around the knot are distorted causing cross grains while discontinuity of wood fiber leads to stress concentrations and checking often occurs around knots in drying (FPL, 2010).

Slope of grain

In some wood product applications, the directions of important stresses may not coincide with the natural axes of fibre orientation in the wood. This may occur by choice in design, from the way the wood was removed from the log, or because of grain irregularities that occurred while the tree was growing (FPL, 2010).

Annual ring orientation

Stresses perpendicular to the fibre (grain) direction may be at any angle from 0^0 (T direction) to 90^0 (R direction) to the growth rings. Perpendicular-to-grain properties depend somewhat upon orientation of annual rings with respect to the direction of stress. The compression perpendicular-to-grain values are derived from tests in which the load is applied parallel to the growth rings (T direction); shear parallel-to-grain and tension perpendicular-to-grain values are averages of equal numbers of specimens with 0^0 and 90^0 growth ring orientations. In some species, there is no difference in 0^0 and 90^0 orientation properties. Other species exhibit slightly higher shear parallel or tension perpendicular-to-grain properties for the 0^0 orientation than for the 90^0 orientation; the converse is true for about an equal number of species (FPL, 2010).

The effects of intermediate annual ring orientations have been studied in a limited way. Modulus of elasticity, compressive perpendicular-to-grain stress at the proportional limit, and tensile strength perpendicular to the grain tend to be about the same at 45^0 and 0^0, but for some species these values are 40% to 60% lower at the 45^0 orientation. For those species with lower properties at 45^0 ring orientations, properties tend to be about equal at

0^0 and 90^0 orientations. For species with about equal properties at 0^0 and 45^0 orientations, properties tend to be higher at the 90^0 orientation.

Reaction wood

Reaction wood refers to abnormal woody tissue which is frequently associated with leaning boles and crooked limbs of both conifers and hardwoods. It is generally believed that such wood is formed as a natural response of the tree to return its limbs or bole to a more normal position, hence the term reaction wood. In softwoods, the abnormal tissue is called compression wood; it is common to all softwood species and is found on the lower side of the limb or inclined bole. In hardwoods, the abnormal tissue is known as tension wood; it is located on the upper side of the inclined member, although in some instances it is distributed irregularly around the cross section (FPL, 2010). Many of the anatomical, chemical, physical, and mechanical properties of reaction wood differ distinctly from those of normal wood. The most evident is the increase in density compared with that of normal wood. The specific gravity of compression wood is commonly 30% to 40% greater than that of normal wood; the specific gravity of tension wood commonly ranges between 5% and 10% greater than that of normal wood, but it may be as much as 30% greater (FPL, 2010).

Juvenile wood

Juvenile wood is the wood produced near the pith of the tree; for softwoods, it is usually defined as the material 5 to 20 rings from the pith depending on species. Juvenile wood has considerably different physical and anatomical properties than that of mature wood. In clear wood, the properties that have been found to influence mechanical behaviour include fibril angle, cell length, and specific gravity, the latter a composite of percentage of latewood, cell wall thickness, and lumen diameter. Juvenile wood has a high fibril angle (angle between longitudinal axis of wood cell and cellulose fibrils), which causes longitudinal shrinkage that may be more than 10 times that of mature wood.

Compression wood and spiral grains are also more prevalent in juvenile wood than in mature wood and contribute to longitudinal shrinkage. In structural lumber, the ratio of modulus of rupture, ultimate tensile stress, and modulus of elasticity for juvenile to mature wood ranges from 0.5 to 0.9, 0.5 to 0.95, and 0.45 to 0.75, respectively. Changes in shear strength resulting from increases in juvenile wood content can be adequately predicted by monitoring changes in density alone for all annual ring orientations. The same is true for perpendicular-to-grain compressive strength when the load is applied in the tangential direction. Compressive strength perpendicular-to-grain for loads applied in the radial direction, however, is more sensitive to changes in juvenile wood content and may be up to eight times less than that suggested by changes in density alone (FPL, 2010). The juvenile wood to mature wood ratio is lower for higher grades of lumber than for lower grades, which indicates that juvenile wood has greater influence in reducing the mechanical properties of high-grade structural lumber. Only a limited amount of research has been done on juvenile wood in hardwood species.

Extractives

Many wood species contain removable extraneous materials or extractives that do not degrade the cellulose lignin structure of the wood. These extractives are especially abundant in species such as larch, redwood, western red cedar, and black locust. A small decrease in MOR and strength in compression parallel to grain has been measured for some species after the extractives have been removed (FPL, 2010). The extent to which extractives influence strength is apparently a function of the amount of extractives, the moisture content of the piece, and the mechanical property under consideration.

Heartwood of most tree species has extractives deposited in them. These extractives have an effect on basic density of wood. Walker (1993) found that heartwood with extractives content has a higher density than the sapwood which makes difference in strength properties. A small decrease in MOR and strength in compression parallel to grain has been measured for some species after the extractives have been removed. The extent to which extractives influence strength is apparently a function of the amount of extractives, the moisture content of the piece and the mechanical property under consideration.

Strain rate

Strain rate is another factor which affects strength properties. Ishengoma and Nagoda (1991) reported that compression parallel to the grain and bending strength increased by 8 percent for every 10 fold increase in strain rate. FPL (201) reviewed that there is a 31 percent increase in MOR for any increase in strain rate of 10^4 x 2.54 cm per minute increase.

2.6.2.5.2 Effects of manufacturing and service environments

Moisture content

Many mechanical properties are affected by changes in moisture content below the fiber saturation point (Figure 1). Generally, most mechanical properties increase as wood is dried. Above the fiber saturation point, most mechanical properties are not affected by change in moisture content. Care should be exercised when adjusting properties below 12% moisture. Although most properties will continue to level, for most species some properties may reach a maximum value and then decrease with further drying (FPL, 2010).

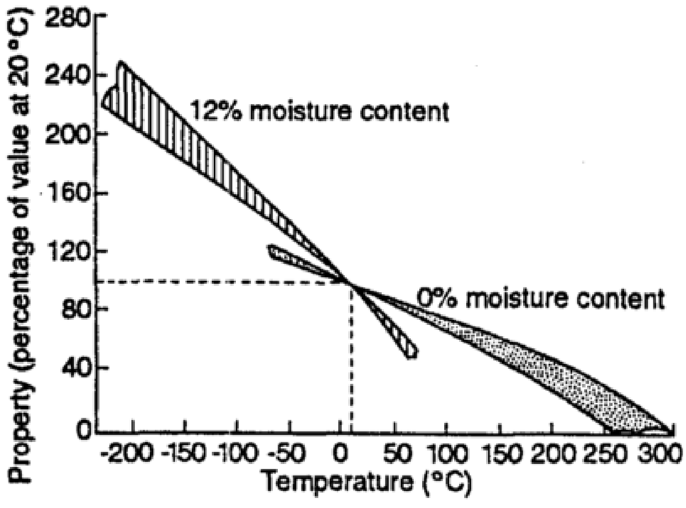

Figure 1: Immediate effect of temperature on bending strength, tensile strength perpendicular to grain, and compression strength parallel to grain. Variability is indicated by the width of bands. Source: FPL (2010)

Temperature

Temperature can have both immediate (reversible) and permanent (irreversible) effects on wood properties. In general, one immediate effect is that mechanical properties tend to decrease as the temperature is increased. There is an interaction with moisture content because dry wood is less sensitive to temperature change than is green wood. However, increases in temperature are usually accompanied by a reduction in moisture content. Permanent loss in mechanical properties can occur if wood is subjected to high temperatures over long periods. The magnitude of this effect depends upon temperature, duration of exposure, wood moisture content and wood property (FPL, 2010).

Exposure to chemicals

The effect of chemical solutions on mechanical properties depends on the specific type of chemical. Nonswelling liquids such as petroleum oils and creosote, have no appreciable effect on properties. Properties are lowered in the presence of water, alcohol, or other wood-swelling organic liquids even though these liquids do not chemically degrade the wood substance. The loss in properties depends largely on the amount of swelling, and this loss is regained upon removal of the swelling liquid. Anhydrous ammonia markedly reduces the strength and stiffness of wood, but these properties are regained to a great extent when the ammonia is removed. Heartwood generally is less affected than sapwood because it is more impermeable. Accordingly, wood treatments that retard liquid penetration usually enhance natural resistance to chemicals (FPL, 2010).

Chemical solutions that decompose wood substance (by hydrolysis or oxidation) have a permanent effect on strength. The following generalizations summarize the effect of chemicals; (i) some species are quite resistance to attack by dilute chemicals and organic acids (ii) oxidizing acids such as nitric acid degrade wood more than non-oxidizing acids (iii) alkaline solutions are more destructive than acidic solutions, and (iv) hardwoods are more susceptible to attack by both acids and alkalies than are softwoods. Because both species and application are extremely important, reference to industrial sources with a specific history of use is recommended where possible. For example, large cypress tanks have survived long continuous use where exposure conditions involved mixed acids at the boiling point (FPL, 2010). Wood is also used extensively in cooling towers because of its superior resistance to mild acids and solutions of acidic salts.

Duration of loading

The duration of load, or the time during which a load acts on a wood member either continuously or intermittently, is an important factor in determining the load that the member can safely carry. The duration of load may be affected by changes in temperature and relative humidity. The constant stress that a wood member can sustain is approximately an exponential function of time to failure (FPL, 2010).

Decay and insect damage

Unlike mold and stain fungi, wood-destroying (decay) fungi seriously reduce strength by metabolizing the cellulose fraction of wood that gives wood its strength. Early stages of decay are virtually impossible to detect. For example, brown-rot fungi may reduce mechanical properties in excess of 10% before a measurable weight loss is observed and before decay is visible. When weight loss reaches 5% to 10%, mechanical properties are reduced from 20% to 80%. Decay has the greatest effect on toughness, impact bending, and work to maximum load in bending, the least effect on shear and hardness, and an intermediate effect on other properties. Thus, when strength is important, adequate measures should be taken to (a) prevent decay before it occurs, (b) control incipient decay by remedial measures, or (c) replace any wood member in which decay is evident or believed to exist in a critical section (FPL, 2010). Decay can be prevented from starting or progressing if wood is kept dry (below 20% moisture content).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study Area Description

The study was conducted in Lushoto, Kibaha, Kwamarukanga and Tabora sites (Table 9 and Figure 2). Lushoto site is located within Lushoto district, Tanga Region. Kwamarukanga site is located within Kwamarukanga forest reserve, Handeni District, Tanga Region. Kongowe-Kibaha site is located within Ruvu North Forest Reserve, Pwani Region. Tabora site is located within Tabora Municipality. Lushoto, Kibaha and Kwamarukanga sites have dry spell between June and September, short rains from October to December and long rains from March to May while Tabora receives long rain between November and April. Four study sites selected were used to represent a wide range of environmental conditions out of 15 experimental sites. The choice of study sites was based on different climatic conditions as most of the trial plots fall under four selected agro-ecological zones.

Table 9: Study area description

Site characteristics	Sites			
	Lushoto	**Kwamarukanga**	**Kibaha**	**Tabora**
Latitude (S)	$04^0$47'15''	$05^0$15'48''	$06^0$42'39''	$04^0$82'86''
Longitude (E)	$38^0$17'40''	$38^0$30'28''	$38^0$52'52''	$32^0$62'97''
Altitude (m.a.s.l)	1393 – 148	70	104	1175
Mean annual rainfall (mm)	1070	1000	900	700 – 1000
Mean temperature (^{0}C)	7 – 30	19 – 32	23 – 35	18 – 28
Soil pH	4.4 – 4.5	3.8 – 4.7	4.5 – 4.9	4.8 – 6.2
Soil Organic carbon (%)	2.7 – 3.6	1.8 – 2.6	0.68 – 1.7	1.7 – 2.9.
Soil texture	Sandy	Sand clay	Sandy	Sandy

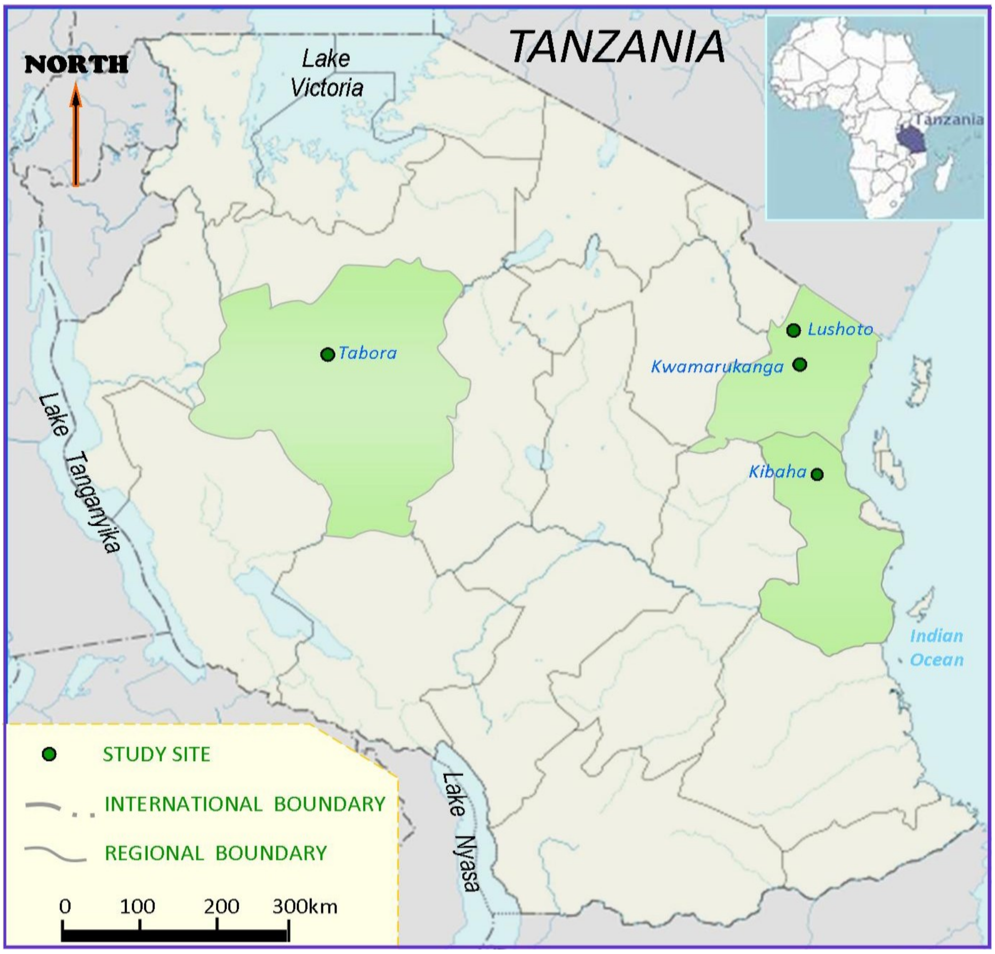

Figure 2: Map of Tanzania showing study sites

3.2 Experimental Design

The experiments were established by TAFORI in 2004 using Eucalypt clonal materials from Mondi South Africa. Randomized complete block design with four replications and 12 treatments (Eucalypt clones) was used to set up these experiments at Lushoto, Kibaha and Kwamarukanga sites and 16 treatments at Tabora site (Table 10). Each clone type was represented once in each block. Each plot comprised 16 trees spaced at 2.5 x 2.5 m in a 4 x 4 arrangement except for Lushoto site which comprised 20 trees in 5 x 4 arrangement and similar spacing.

The experiments have 2 guard rows planted to avoid edge effect. The experimental plots were fenced following planting to keep off small game and other intruders. A termitecide was added to wad off termites. Weeding was done whenever grass threatened to overtop the planted seedlings. Silvicultural management and previous growth assessments were carried out by TAFORI.

Table 10: Experimental design of Eucalypt clones

Blocks	Eucalypt clones (Treatments)											
B4	GC 940	GC 14	**GC** 10	GC 167	GC 581	GC 584	GT 529	GC 796	GU 608	GC 15	GC 785	GC 514
B3	GC 14	GT 529	GC 796	GC 584	GC 15	GU 608	GC 514	GC 785	GC 10	GC 167	GC 940	GC 581
B2	GC 785	GC 15	GU 608	GT 529	GC 581	GC 940	GC 10	GC 14	GC 514	GC 796	GC 584	GC 167
B1	GC 10	GT 529	GC 581	GU 608	GC 514	GC 785	GC 14	GC 167	GC 584	GC 940	GC 796	GC 15

3.3 Data Collection

Previous data on diameter at breast height (Dbh), survival and height of trees were collected in 2006, 2007, 2008 and 2009. In this study, data on survival, Dbh, height and above ground biomass were collected at the age of 8 years in 2012. Data on physical and mechanical properties of wood and water use were collected in 2013 at 9 years and in 2014 at 10 years respectively.

3.3.1 Determination of growth performance of Eucalypt clones

3.3.1.1 Growth assessment

Data on survival, Dbh, height and aboveground biomass were collected in 2012. Height was measured using Suunto hypsometer while Dbh was measured using a diameter tape. The tally of diameter growth also gave tree survival data. All trees in the plot were measured for Dbh, while 6-12 trees per plot (small, medium and large size) were measured for height (Mugasha *et al.,* 1996; Delgado-Matas and Pukkala, 2011).

The Dbh measurements were used to calculate the mean plot basal area. Basal area was derived by summing the individual basal areas of trees within a plot and then the plot basal areas were computed by summing basal area of individual trees in a plot. To obtain basal area per ha (m^2 ha^{-1}), plot basal areas were divided by plot area in ha. Height, Dbh and survival data were first used to determine three best performers in each studied site.

3.3.1.2 Sampling and laboratory procedures for volume and biomass determination

Three superior Eucalypt clones in terms of survival, Dbh and height (i.e. GC 581, GC 584 and GU 608 for Lushoto site; GC 15, GC 167 and GC 940 for Kibaha site; GC 514, GT 529 and GC 940 for Kwamarukanga site and GC 15, GC 584 and GC 940 for Tabora site) were selected. Subjective sampling was applied to select thirty trees (<10 cm, 10-20 cm and >20 cm) from three clone type at each site for volume and above ground biomass determination. Before felling, trees were measured for Dbh and height and the total length of the tree were measured after felling. Sampled trees were divided into two main parts: aboveground and belowground. The aboveground part was considered as all biomass above a stump height of 15 cm which was further divided into sections namely stem, branches including tops (up to a minimum diameter of 2 cm) and twigs (with diameter less than 2 cm).

Stems and branches were trimmed and cross cut into manageable billets ranging from 1 to 1.5 m in length (Saint-Andre´*et al.,* 2005; Heriansyah *et al*., 2007). Mid diameter and length of each billet were measured for volume determination. Three sample discs from stem and one disc sample from branches (about 2 cm thick cut from bark to pith) were extracted and weighed. Stem and branch billets were then weighed and the green weight recorded. Twigs were collected into separate bundles and the green weight of each was taken. Leaves were also collected and the green samples were weighed. The total fresh weight of each component was taken in the field using a balance.

Stem, branch and twig samples were oven dried to constant weight at 103± 2^0C while leaves were oven dried at 70^0C for 48 hours and after that changes in weight were monitored at intervals of 6 hours until there was no change in weight. The wooden blocks from the stem, branch billets and twigs were soaked in water for one week and then measured for green weight using kitchen scale. The volume of each wood block was determined by water displacement method (West, 2004). Biomass was determined using biomass ratios of sample trees and were computed as the ratio of oven dry weight to the green weight for each tree component namely whole tree, stems, branches, twigs and leaves.

3.3.1.3 Determination of tree volume

Huber's formula ($\pi r^2 L$) was employed for volume determination (West, 2004). Total tree volume was calculated as the summation of individual stem and branch billets volumes. Then, mean annual increment (MAI) for volume was calculated using the following relationship.

$$MAI\ (m^3ha^{-1}yr^{-1}) = \frac{Y(t_2) - Y(t_1)}{t_2 - t_1} \quad \text{.........(1)}$$

Where

$Y(t_2)$ = Volume production of the second year

$Y(t_1)$ = Volume production of the first year

t_2 = Second year

t_1 = First year

Thereafter, site specific volume model was developed and used (Table 11).

3.3.1.4 Model development, selection and evaluation

The biomass for each tree component was computed as the product of biomass ratio and total fresh weight. Site specific models for above ground biomass, stem biomass and volume were developed. Models predicting biomass and volume were based on Dbh only, and on a combination of Dbh and height, as independent variables. Numerous model forms have previously been applied when developing biomass models (Zianis *et al.,* 2005; Henry *et al.,* 2011, Mugasha *et al.,* 2013). Four model forms for prediction of biomass (dry weight), which have been commonly adopted previously was tested (Equation 2, 3, 4 and 5). Two of the model forms include Dbh only and two include height in addition.

$Y = \beta_0 dbh^{\beta 1}$ (Model form 1)... (2)

$Y = Exp\ (\beta_0 + \beta_1 ln\ (htxdbh^2)$ (Model form 2)... (3)

$Y = \beta_0 dbh^{\beta 1}\ ht^{\beta 2}$ (Model form 3)... (4)

$Y = \beta_0 + \beta_1 dbh + \beta_2 dbh^2$ (Model form 4)... (5)

Where

Y = Biomass (kg) or Volume (m^3)

Dbh = Diameter at breast height (cm)

Ht = tree total height (m)

β_0 β_1 and β_2 are regression coefficients.

The best-fit models were selected based on the Akaike Information Criterion (AIC) (Equation 6). AIC takes into account the number of parameters in the models and penalizes them accordingly (Mugasha *et al.,* 2013). R^2 reported for all tested models were not used as criteria for selecting final models because the tested model forms had different numbers of parameters. With an increase in number of parameters, a model tends to have larger R^2 values regardless of their contribution in explaining the variation in the response variable. Models with insignificant parameter estimates were excluded during the selection process irrespective of AIC values. All models were analysed using Non Linear Programming (NLP) procedure in SAS programme to estimate the model parameters (βo, β_1, and β2). The procedure produces the least squares estimates of the parameters of a nonlinear model through an iteration process. Goodness of fit and model comparisons was evaluated using bias percents. Models with lower bias and AIC were selected and used to predict total volume and tree biomass for trees sampled at Lushoto, Kibaha, Kwamarukanga and Tabora sites (Table 11).

AIC = 2k – 2 In (L) …………………………….…………………………….………….. (6)

Where: k = number of parameters in the statistical model

L = maximized value of the likelihood function for estimated model

Table 11: Final weighted equations for the aboveground biomass and volume model

Sites	Biomass model	R^2	AIC
Lushoto	Y=0.1274*Dbh^2.6110	0.95	290.53
Kibaha	Y=0.1379*Dbh^2.4369	0.93	256.71
Kwamarukanga	Y=0.4124*Dbh^2.1128	0.9	256.75
Tabora	Y=0.7759*Dbh^1.7913	0.9	236.84
	Volume model		
Lushoto	Y=0.000324*Dbh^2.3988	0.96	61.03
Kibaha	Y=0.000311*Dbh^2.2087	0.96	78.4
Kwamarukanga	Y=0.000628*Dbh^2.07599	0.90	69.66
Tabora	Y=0.000811*Dbh^1.8565	0.94	87.08

3.3.2 Determination of water use by Eucalypt

Selection of clones for sap flow measurements were based on their growth performance in terms of survival, Dbh, height, basal area, volume and biomass production. In this case, GC 167, GC 940 and GC 15 were selected for measuring water use in two seasons (wet and dry season). Subjective sampling was applied to select three trees, one tree from each clone type for water use measurements (Cavaleri *et al.,* 2014). Data were collected from 30th April and ended on 5th June 2014 in wet season while those for dry season they were collected from 13th August and ended on 3rd October 2014. Heat pulse velocity (HPV) was used to estimate whole tree water use for Eucalypt clones (Plate 1). A pulse of heat is injected into the xylem and the velocity of its travel to a point further along the direction of flow is used to estimate sap flow velocity (Simpson, 2000). Probes were inserted into holes drilled radially into the trunk and aligned along the trunk axis (Burgess *et al.,* 2001). A drilling jig was used to ensure that the holes drilled were parallel to one another (Dye *et al.,* 1996) and at the correct vertical spacing. The probes consisted of two thermistors, one 10 mm upstream and one 5 mm downstream from a heater at the centre (Figure 3).

Plate 1: Installed HRM 30 sap flow metre for tree water use measurement

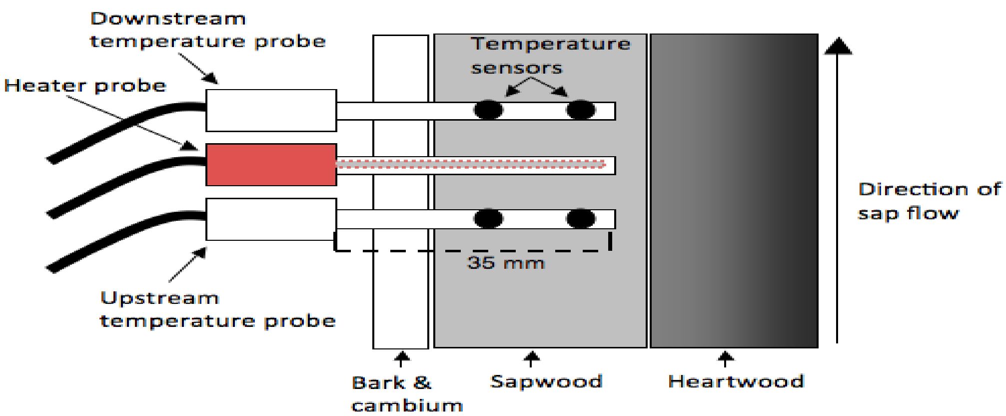

Figure 3: Schematic view of HRM30 components installed in trees to determine sap flow velocity

Probes were installed in holes drilled horizontally into the sapwood at a height of 1m (Dye *et al.,* 1996). The upper and lower thermistors were used to detect the convective and conductive heat fluxes respectively, after a short (0.5-1.5 s) heat pulse. Each thermistor contains two temperature sensors, facilitating simultaneous measurement of sap velocity at two different depths in the sapwood (Dye *et al.,* 1996). Sensors were coated with silicon vacuum grease before insertion to improve thermal contact with the xylem and to aid both installation and removal of needles.

HPV (cm h^{-1}) were collected automatically every 30 minute intervals then averaged over 1 hr for each probe set (Swanson and Whitfield, 1981) and stored in an electronic data logger before being downloaded to a computer.Then, sap velocity (V_{si}) was calculated according to the procedures outlined in Swamson and Whitfield (1981). The following relationship was used to calculate sap velocity (V_{si}) as:

$$V_{si}\ (\text{cm hr}^{-1}) = \frac{k \times B \times \rho b\ (C_w + M_c \times C_s) \times V_{hi}}{0.0025 \times \rho s \times C_s} \quad \text{.......................................} (7)$$

Where

k is the thermal diffusivity (cm² s–¹), 0.0025 the reference thermal diffusivity (cm² s–¹), B the wound correction factor (-), ρb the basic density of wood (sapwood dry weight/sapwood fresh volume, kg m–³), Cw the specific heat capacity of the wood matrix (1200 J kg–¹ °C–¹), Cs the specific heat capacity of sap (water, 4182 J kg–¹ °C–¹), ρs the density of water (1000 kg m–³), Mc the water content of sapwood (sapwood fresh weight - sapwood dry weight)/sapwood dry weight, kg kg–¹) and V_{hi} the measured heat pulse velocity (cm h–¹) at position i (Swanson and Whitfield, 1981).

Sapwood area determination

Sapwood area, volume, thickness and wood density were determined by extracting a perpendicular core from each of the sample trees. The inner and outer boundary of sapwood is generally easily seen by a distinct colour change at the cambium sapwood boundary and the sapwood heartwood boundary. Knowing the inner and outer diameter of the sapwood allows calculation of the area of each individual tree. Sapwood area declines with stand age (Haydon *et al.,* 1996).

Methyl Orange in a standard mixing concentration of 0.1% solution (indicator dye) is applied and left for approximately 15 minutes on the sample, allowing the sample to stain and differentiate the sapwood from the heartwood (the actively conducting xylem of the sapwood and the non-conducting xylem of the heartwood). The lighter coloured area is the sapwood and the dark region is the heartwood. The heartwood stains darker due to the build-up of tannins associated with the lignification process of heartwood. Then a ruler was used to precisely measure the radial depth or thickness of the sapwood. Table 12 shows the parameters used to calculate Eucalypt clones water use.

Table 12: Parameters used for Eucalypt clones water use at Kongowe - Kibaha

Variables measured	**Treatments**		
	GC 167	**GC 15**	**GC 940**
Dhb (cm)	24.5	21	19
Bark thickness (mm)	12	6	6
Sapwood depth (cm)	3.6	2.5	2.7
Sapwood fresh weight (g)	0.271	0.266	0.200
Sapwood dry weight (g)	0.237	0.226	0.182
Sapwood volume (cm^3)	0.481	0.451	0.358
Sapwood area (cm^2)	209.23	135.78	133.17

Sapwood area (A_{sw}) is then calculated using the following equation;

$$A_{sw} = \pi \, (r_{sw}+_{hw})^2 - \pi \, (r_{hw})^2 \quad \ldots\ldots (8)$$

Where

r_{sw+hw} is the radial thickness of the sapwood plus the heartwood, and r_{hw} is the radial thickness of the heartwood (all in cm) (Cavaleri *et al.,* 2014).

Therefore;

Mean daily water use is calculated using the following relationship;

Water use (L day^{-1}) = V_{si} x A_{sw} ……………………………………………...………… (9)

Weather data collection

Rainfall and temperature were recorded daily at Kongowe, Kibaha weather station by using rain gauge and glass thermometer respectively. Daily rainfall, minimum and maximum temperatures data were used to plot graphs showing climate trends for two seasons (dry and wet).

3.3.3 Determination of wood properties

3.3.3.1 Sample selection

Wood samples were obtained from three superior Eucalypt clones in terms of survival, Dbh, height, basal area, volume and biomass production (i.e. GC 581, GC 584 and GU 608 from Lushoto site; GC 15, GC 167 and GC 940 from Kibaha site; GC 514, GT 529 and GC 940 from Kwamarukanga site and GC 15, GC 584 and GC 940 from Tabora site. Subjective sampling was applied to select three trees (small, medium and large in Dbh) from each clone type. In total, 36 trees were felled and cut into logs for physical and mechanical properties determination. The properties of wood of Eucalypt clones determined were wood basic density, fibrer length and strength namely MOE, MOR, radial and tangential cleavage, compression parallel to the grain and shear parallel to the grain. The dimensions of test specimens for different tests are presented in Table 13.

Table 13: Test specimen dimensions for wood properties

Property	Specimen dimensions (mm)	Number of samples per clone type	Total number of specimens
Basic density	20 x 20 x 10	36	432
Fibre length	20 x 20 x 20	36	432
MOE and MOR	20 x 20 x 300	36	432
Compression parallel to the grain	20 x 20 x 20	36	432
Shear parallel to the grain	20 x 20 x 60	36	432
Cleavage in radial and tangential	20 x 20 x 45	72	864

3.3.3.2 Physical properties

3.3.3.2.1 Determination of wood basic density

Stem sectional discs measuring 5 cm thick were taken from each log at breast height (1.3 m), 25% and 50% of tree height (Hashemi and Kord, 2011). A wedge running from pith to bark was cut from each disk. Samples were cut at 25% and 50% of wedges' total length. Basic density (BD) was determined in accordance with procedure described in BS 373 (1957), Lavers (1969) and ISO 3131 (1975). All specimens were soaked in distilled water till they attained green volume condition. Green volume was obtained using the displacement method in accordance with Archimedes' principle (Olesen, 1970). The test specimens were then oven dried at a temperature of 103 ± 2°C until constant weight and then cooled in desiccators. The specimens were reweighed and the weights recorded. BD in Kg m^{-3} was then calculated using the following relationship:

BD (Kg m^{-3}) = [Oven dry weight (grammes) /Green volume (cm^3)] × 1000 ……..….(10)

3.3.3.2.2 Determination of fibre length

Fibre length splinters measuring 2 x 2 x 10 mm were taken from each tree at different levels at breast height (1.3 m), 25% and 50% of tree height. Fibre lengths were determined using standard procedure described by Panshin and de Zeeuw (1980).

Splinters were then macerated using 1:1 glacial acetic acid and hydrogen peroxide at about 60^{o}C for 48 hours for cell dissociation. After maceration, splinters were washed with distilled water and then shaken gently in the distilled water until individual fibres of the wood were separated. The macerated fibres were thoroughly mixed and then stained with safranin solution and spread on a glass slide. Thirty straight and unbroken fibres from each sample were randomly selected for measurement using a projecting microscope to obtain a mean fibre length (Sadegh and Kaei, 2011) for each Eucalypt clone.

3.3.3.3 Mechanical properties

Each log was cross cut into three 1.5 m long billets at breast height (1.3 m), 25% and 50% of the tree height and each billet was sawn into 45 - 65 mm thick radial planks for easy air drying and labeled to indicate tree number and position in the tree. The planks were re- sawn radially into 30 mm x 60 mm x 1500 mm planks. Planks were air dried to about 12% moisture content and re-sawn into 20 x 30 x 1500 mm scantlings which were then planed to 20 mm x 20 mm x 1500 mm. Test specimens were obtained from these planks in accordance with ISO 3129 (1975).

3.3.3.3.1 Determination of MOE and MOR

MOE and MOR were determined according to the standard procedures described by ISO 3349 (1975) for MOE and ISO 3133 (1975) for MOR. Specimens measuring 20 x 20 x 300 mm were taken and loaded using centre loading method to the Monsantor Tensiometer wood testing machine using a feeding speed of 0.635 mm/min and 500 kg deflection beam. Graph plotting was done manually following the mercury column along the scale in Newton. The load at which failure occurred was recorded on graph paper. MOR was calculated from the maximum load at which each specimen failed. MOE was calculated using load to deflection curve plotted on a graph by the machine. MOE and MOR were calculated using the following relationship.

MOR ($N\ mm^{-2}$) $=3PL/2BD^2$……………………………………………………(11)

MOE ($N\ mm^{-2}$) $=P^1L^3/4YBD^3$……………………………………………………(12)

Where

P	=	Maximum load in Newton's (N)
L	=	Span length (mm)
B	=	Width of the test sample (mm)
P^1	=	Load in Newton's to limit of proportionality
D	=	Depth of the test sample (mm)
Y	=	Deflection in mm at mid length at limit of proportionality

3.3.3.3.2 Determination of radial and tangential cleavage

Cleavage strength was determined according to the standard procedure described by Panshin and de Zeeuw (1980). Test specimens measuring 20 x 20 x 45 mm were taken and then mounted on the Monsanto Tensiometer machine with a loading speed of 2.5 mm/min and a beam of 500 kg. The graph was manually plotted by following the rise of mercury along its column until failure occurred. Maximum cleavage load was recorded at the point of failure. Cleavage strength was calculated by using the following relationship:

Cleavage strength ($N\ mm^{-2}$) $= \frac{P_{(max)}}{B}$……………………………………………………(13)

Where

P = Maximum load (N)

B = Specimen width (mm)

3.3.3.3.3 Determination of compression strength parallel to the grain

Compression strength parallel to the grain was determined according to the standard procedure described by ISO 3787 (1976). Each test specimen measuring 20 x 20 x 60 mm was loaded on a parallel grain basis to the Monsanto Tensiometer machine using a feeding speed of 0.635 mm/min and 2000 kg deflection beam. Then, the maximum crushing load was recorded by plotting the graph following the rise of the mercury in the column until failure occurs. The maximum crushing strength was then calculated from maximum crushing load and recorded in N/mm^2. Crushing strength was calculated using the following relationship:

$$\text{Compression strength (N mm}^{-2}\text{)} = \frac{P_{(max)}}{A} \quad \text{.......(14)}$$

Where $P_{(max)}$ = Maximum crushing load in Newton's (N)

A = Cross-sectional area (mm^2)

3.3.3.3.4 Determination of shear strength parallel to grain

Shear strength parallel to grain test was determined according to the standard procedure described by ISO 3347 (1976). Each test specimen measuring 20 x 20 x 20 mm was mounted on the Monsanto Tensiometer machine with a 2000 kg deflection beam and a speed of 0.635 mm/min was used. Maximum shear strength was recorded graphically straight from the rise of the mercury along the column until failure occurred. Shear strength was calculated using the following relationship:

$$\text{Shear strength at maximum load (N mm}^{-2}\text{)} = \frac{P}{A} \quad \text{....... (15)}$$

Where; P = Maximum load (N)

A = Area in shear (mm^2)

Strength values were corrected (transformed to 12% moisture content) using the following strength conversion equation:

$\delta_{12} = \delta_m * [1 + \alpha (W - 12)]$ ....(16)

Where,

δ_{12} = strength at 12 percent moisture content ($N\ mm^{-2}$)

W= moisture content during test (%)

δ m = strength at moisture content deviated from 12 percent (Nmm^{-2})

α = constant value showing relationship between strength and moisture content

(α = -0.02, 0.04, 0.04, and 0.04 and for MOE, MOR, compression and shear parallel to grain respectively) (Ishengoma and Nagoda, 1991).

3.4 Data Analysis

3.4.1 Growth performance

3.4.1.1 Growth assessment

For each tree variable namely Dbh (cm), height (m), basal area (m^2ha^{-1}), survival (percent), volume (m^3ha^{-1}), MAI ($m^3ha^{-1}yr^{-1}$) and biomass ($t\ ha^{-1}$), data were analysed using the General Liner Model (GLM) procedure from the SAS System to get clone means. Analysis of variance was used to determine significant difference at 95% significance level between Eucalypt clones within a site. Clone means showing significantly differences were separated by Duncan's Multiple Range Test (DMRT). Model for estimating height was developed using equation 17 below (Schreuder *et al.,* 1979) where the height of trees which were not measured were predicted.

Height estimates

$H = 1.3 + a*Dbh^b$ ………………….………….……………………… (17)

Where:

H = Total tree height (m)

a and b = parameters to be estimated

Dbh = Diameter at breast height (cm)

1.3 = Constant used to account that Dbh is measured at 1.3 m above ground.

3.4.1.2 Ordinal ranking

An ordinal ranking scheme was devised to differentiate overall performance for each clone type when significantly different growth was found. Ranking of treatments in six tree parameters namely survival, height, Dbh, basal area, volume and biomass production was used. Each variable which showed significant variation, 1 point was assigned for the best value and 12 points for the worst for Lushoto, Kibaha and Kwamarukanga sites or 18 points for Tabora site. Ranks were added, averaged and the overall score was taken as a basis of the overall clone performance ranking.

3.4.2 Water use by Eucalypts

All statistical tests were performed using Sap flow tool software version 1.4 (SFT, 2013). ANOVA was used to compare daily water use between clones. DMRT was used to separate means of daily water use between clones. Correlation was carried out to determine the influence of temperature on water use

3.4.3 Wood properties

3.4.3.1 Physical properties

Data were analysed using SAS software version 9.1 for windows. ANOVA was used to compare wood basic density and fibre length between Eucalypt clones at 95% significance level. Significantly different clones' means were separated by DMRT.

Simple linear regression analysis was employed to determine the relationship between Dbh and wood basic density of the clones. The coefficient of determination "R^2" was used to verify the suitability of the regression equations for each observation.

3.4.3.2 Mechanical properties

Data were analysed using SAS software version 9.1 for windows. Analysis of variance was used to compare the MOE, MOR, cleavage, compression and shear strength between Eucalypt clones. Significantly different clones' means were separated by using DMRT.

3.5 Limitations of the Study

i. Study design: the study did not include local Eucalypt land races for comparison with the improved clones.

ii. Data limitations: Previous data on growth performance of Eucalypt clones in some sites for some years were missing. To overcome this problem, years with complete data set were used to show the trend of growth performance of Eucalypt clones at the study sites.

iii. Lack of equipped meteorological station for measuring weather parameters such as solar radiation, wind speed, air temperature and air humidity. These are principal weather parameters affecting evapotranspiration. To overcome this problem, data on temperature and rainfall were recorded at the studied site. These data were used to show their influence on the amount of water used by Eucalypt clones.

iv. Water use by Eucalypt clones study was designed to be carried out in all study sites. However, due to high cost of water use equipment, only one set of equipment could be purchased for one site. Kibaha site was used to conduct this study in wet and dry seasons. Kibaha site is close for easy consultation with experts at SUA. This study provides preliminary results which will be used as baseline information for water use by Eucalypt clones in Tanzania.

v. There was illegal cutting and fire at Tabora sites, and this influenced stocking estimates.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Growth Performance

Growth performance of Eucalypt clones was studied at Lushoto, Kibaha, Kwamarukanga and Tabora sites based on the following growth parameters: survival, Dbh, height, basal area, volume, MAI and biomass production. In the following sections, results on these parameters are presented and discussed.

4.1.1 Survival, diameter and height growth of Eucalypt clones

4.1.1.1 Survival

Table 14 shows the survival of Eucalypt clones for all study sites. The results revealed that clones at Lushoto site survived better and the survival was much higher for GC 10, GC 15, GC 167, GC 785 and GC 796 which achieved 100% survival rates. At Kwamarukanga site, GC 940, GT 529 and GC 514 were the best survivors with survival of 98.44%, 97.10% and 96.98% respectively compared to the rest of the clones. At Kibaha site, GC 940, GC 15 and GT 529 had highest survival of 76.34%, 66.88% and 62.08% respectively over the other clones. At Tabora site, survival of 60.94% and 51.56% was recorded for GC 940 and GC 584 respectively. Other clones on this site had less survival percentages. Results from other studies revealed that the survival of majority of clonal plantations for example in India is more than 95% (Kulkarni and Lal, 1995; Drumond *et al.,* 2012). Results from the present study show significant ($p<0.05$) differences in survival between Eucalypt clones within a site in all the study sites. The difference in survival between clones within a site was probably a result of genetic differences between the clones which interact differently with the various climatic and soil conditions.

Table 14: Survival of 8 year old Eucalypt clones from four sites

Treatment	Survival (%)			
	Lushoto	Kwamarukanga	Kibaha	Tabora
GC 10	100.00a	41.32fg	34.38f	40.63bc
GC 14	99.08a	42.28f	50.89de	43.75bc
GC 15	100.00a	93.95bc	66.88ab	39.06bcd
GC 167	100.00a	95.98abc	54.89cd	35.94bcd
GC 514	84.52e	96.98ab	58.33bcd	42.19bc
GC 581	98.89a	89.22d	31.70f	7.81g
GC 584	99.05a	95.13abc	61.75bc	51.56b
GC 785	100.00a	92.19cd	44.29e	17.19fg
GC 796	100.00a	75.23d	20.31g	-
GC 940	93.75b	98.44a	76.34a	60.94a
GT 529	91.52c	97.10ab	62.08bc	-
GU 608	88.68d	37.5g	33.52f	4.69gh
GC 3	-	-	-	17.19f
GC 522	-	-	-	7.81g
GC 746	-	-	-	28.13 df
GC 962	-	-	-	34.38cd
GU 125	-	-	-	1.56h
GU 21	-	-	-	34.38cd

Mean values in the same column with same following letters do not differ significantly (p> 0.05) based on DMRT.

The varied survival trends between clones within a site showed a strong environment clone interaction, an observation supported by Wamalwa *et al*. (2007) and Arya *et al.* (2009). For Tabora site, low survival was probably due to fire outbreak which occurred in 2009 and other human disturbances. Survival in general is influenced by several factors, which include site management, especially the weeding frequency and the protection of the seedlings from pests and diseases, drought and seedling handling during planting period (Kahunyo, 2008).

4.1.1.2 Diameter growth

Table 15 presents Dbh growth of various Eucalypt clones at Lushoto, Kwamarukanga, Kibaha and Tabora sites. The results reveal that clones GU 608, GC 584 and GC 581 had the best performance in Dbh at Lushoto site while the least were GC 785, GC 796 and GT 529. At Kibaha site, higher mean Dbh was recorded for clones GC 796, GU 608 and GC 15 when compared to clones GT 529, GC 14 and GC 10. At Kwamarukanga site, higher mean Dbh was recorded for clone GC 514, GT 529 and GU 608 outperformed GC 785, GC 796 and GC 10. At Tabora site, the results revealed that clone GC 581, GU 125 and GU 21 performed relatively better in terms of mean Dbh than GC 514, GC 785 and GU 608.

Table 15: Mean Dbh of 8 year old Eucalypt clones from four sites

	Dbh (cm)			
Treatment	**Lushoto**	**Kwamarukanga**	**Kibaha**	**Tabora**
GC 10	14.74def ± 0.35	11.15b ±0.29	12.44g ±0.38	13.27abcd ± 0.73
GC 14	14.53f ±0.30	11.53ab ±0.35	13.30fg ±0.54	12.56abcd ±0.70
GC 15	15.71bcd ±0.20	12.09ab ±0.38	15.59abc ±0.30	13.38abcd ±0.54
GC 167	15.60bcde ±0.32	11.19b ±0.34	15.27abcd ±0.49	13.21abcd ±0.59
GC 514	15.08cdef ±0.39	12.61a ±0.28	15.09bcde ±0.38	10.99cd ±0.74
GC 581	16.05bc ±0.22	11.16b ±0.32	14.23cdef ±0.68	16.98a ±2.46
GC 584	16.14b ±0.20	12.18ab ±0.28	14.94bcdef ±0.41	13.29abcd ±0.38
GC 785	14.35f ±0.31	11.01bc ±0.34	13.73defg ±0.39	11.41bcd ±0.68
GC 796	14.38f ±0.37	9.99c ±0.41	16.7a ±1.27	-
GC 940	14.67ef ±0.43	12.50a ±0.23	14.86bcdef ±0.27	13.82abcd ±0.63
GT 529	14.46f ±0.39	12.56a ±0.27	13.53efg ±0.36	-
GU 608	19.15a ±0.41	12.52a ±0.75	15.95ab ±0.89	10.00d ±1.52
GC 3	-	-	-	12.84abcd ±1.25
GC 522	-	-	-	11.60bcd ±1.18
GC 746	-	-	-	10.29cd ±1.39
GC 962	-	-	-	13.11abcd ±1.14
GU 125	-	-	-	15.00abc ±0.12
GU 21	-	-	-	15.92ab ±1.13

Values are mean with ±standard error. Values in the same column with same following letters do not differ significantly (p> 0.05) based on DMRT.

Similarly, significant differences in Eucalypt clones have been reported by various researchers. For example, Arya *et al.,* 2009 and Kumar and Bangarwa (2006) observed significant differences for growth attributes among seven species of Eucalypt clones and found that, Indian clones had higher promising performance for Dbh than the results of this study. These differences in Dbh between clones within a site may be attributed to genetic difference (Wamalwa *et al.,* 2007).

Similar trends have been reported by various researchers. For example, Bernhard-Reversat (2001) in Congo reported that a 7 year old Eucalypt plantation had a mean Dbh of 14 to 16 cm; Kirongo *et al.* (2008) reported mean Dbh of 14.78 cm for 5 year old

Eucalypt clones at coastal forests of Kenya; Neilan and Thompson (2008) reported mean Dbh of 13 cm of 8 year old *Eucalyptus nitens* in coastal Ireland while Qader *et al.* (2014) reported diameter growth ranging from 11.2 cm to 14.56 cm for 6 year old Eucalypt clones in North Iraq. Significant ($p < 0.05$) differences in Dbh were noted for clones at Lushoto, Kwamarukanga, Kibaha and Tabora sites. Differences in Dbh growth between clones within a site may be attributed to genetic differences (Wamalwa *et al.,* 2007).

Tables 16 and 17 present MAI for diameter for Eucalypt clones in the four sites studied. The differences in MAI for Dbh of different clones were found to be significant at $p<0.05$ for clones at Lushoto and Kibaha sites while clones at Kwamarukanga and Tabora sites showed no significant differences. As shown in Tables 16 and 17, MAI for Dbh recorded ranged between 0.83 cm yr^{-1} and 2.09 cm yr^{-1} for clones at Lushoto site, 1.79 to 3.19 cm yr^{-1} for Kibaha site, 1.07 cm yr^{-1} to 1.58 cm yr^{-1} for Kwamrukanga site and 2.98 cm yr^{-1} to 5.61 cm yr^{-1} for Tabora site.

Table 16: Periodic Dbh increment of Eucalypt clones at Lushoto and Kwamarukanga sites

Treatment	Lushoto site				Kwamarukanga site				
	Dbh increment			MAI	Dbh increment				MAI
	2008	2009	2012	(cm yr^{-1})	2007	2008	2009	2012	(cm yr^{-1})
GC 10	1.44ab ±0.15	0.16a ±0.08	1.98bcd ±0.10	1.19bc ±0.05	3.56a ±0.20	0.01d ±0.06	0.37d ±0.07	0.75a ±0.22	1.17cd ±0.08
GC 14	1.5ab ±0.11	0.43a ±0.13	1.52bcd ±0.06	1.15bcd ±0.07	2.81bcd ±0.38	0.67abc ±0.34	0.54cd ±0.13	1.59a ±0.14	1.42abc ±0.06
GC 15	1.58ab ±0.10	0.05a ±0.09	2.16bc ±0.09	1.26bc ±0.03	3.57a ±0.37	0.67abc ±0.42	0.78abcd ±0.33	0.72a ±0.05	1.44abc ±0.06
GC 167	1.59ab ±0.12	0.29a ±0.16	1.63bcd ±0.06	1.17bc ±0.05	3.12ab ±0.07	0.15cd ±0.05	0.75abcd ±0.08	0.89a ±0.08	1.22cd ±0.04
GC 514	1.15b ±0.08	0.01a ±0.00	2.33b ±0.06	1.16bcd ±0.03	2.93bc ±0.44	1.10ab ±0.42	0.89abcd ±0.34	1.24a ±0.05	1.58a ±0.03
GC 581	1.88a ±0.08	0.03a ±0.01	1.96bcd ±0.13	1.30bc ±0.04	2.95bc ±0.40	0.68abc ±0.32	0.66bcd ±0.06	0.64a ±0.04	1.22cd ±0.03
GC 584	1.87a ±0.09	0.03a ±0.05	2.21b ±0.04	1.37b ±0.03	2.99bc ±0.35	0.80abc ±0.52	1.06abc ±0.18	1.34a ±0.07	1.55ab ±0.05
GC 785	1.68ab ±0.14	0.15a ±0.13	1.15cd ±0.06	0.99cd ±0.04	2.50cde ±0.19	0.42bcd ±0.19	0.77abdc ±0.10	1.22a ±0.15	1.23cd ±0.08
GC 796	1.45ab ±0.20	0.02a ±0.19	1.03d ±0.07	0.83d ±0.06	2.37de ±0.11	0.35cd ±0.32	0.69bcd ±0.02	0.64a ±0.09	1.07d ±0.13
GC 940	1.30ab ±0.13	0.01a ±0.00	2.01bcd ±0.08	1.09cd ±0.02	3.25ab ±0.49	0.86abc ±0.40	0.80abcd ±0.10	1.26a ±0.04	1.54ab ±0.09
GT 529	1.36ab ±0.37	0.01a ±0.00	2.04bcd ±0.04	1.14bcd ±0.13	3.30ab ±0.51	0.77abc ±0.46	1.29a ±0.32	0.57a ±0.18	1.48abc ±0.06
GU 608	1.72ab ±0.08	0.02a ±0.00	4.51a ±0.14	2.09a ±0.07	2.07e ±1.05	1.28a ±0.65	1.23ab ±0.29	1.25a ±0.12	1.41abc ±0.28

Values are mean with ±standard error. Mean values in the same column with same following letters do not differ significantly ($p > 0.05$) based on DMRT.

Table 17: Periodic Dbh increment of Eucalypt clones at Kibaha and Tabora sites

Treatment	Kibaha site Dbh increments 2007	2008	2009	2012	MAI (cm yr^{-1})	Tabora site Dbh increment 2008	2012	MAI (cm yr^{-1})
GC 10	2.68d±0.25	1.39bcd ±0.23	0.54a ±0.06	0.40f ±0.06	1.83b ±0.15	2.13abc ±0.23	5.44a ±0.00	3.79a ±0.15
GC 14	2.94cd ±0.16	1.03d ±0.09	0.69a ±0.23	0.73a ±0.14	2.08b ±0.10	2.83a ±0.09	4.01a ±0.28	3.42a ±0.11
GC 15	3.78ab ±0.41	1.36bcd ±0.19	0.92a ±0.07	2.13abc ±0.04	2.11b ±0.16	2.13abc ±0.19	4.57a ±0.21	3.35a ±0.11
GC 167	3.33abcd ±0.25	1.53bcd ±0.21	0.92a ±0.28	2.43ab ±0.13	2.19b ±0.12	1.91abc ±0.21	5.67a ±0.22	3.79a ±0.04
GC 514	3.29abcd ±0.30	1.52bcd ±0.33	1.06a ±0.19	2.45ab ±0.10	2.17b ±0.19	1.74abc ±0.33	6.37a ±0.10	4.06a ±0.12
GC 581	2.80d ±0.30	1.99bc ±0.16	1.00a ±0.32	0.95ef ±0.11	2.24a ±0.27	2.62ab ±0.16	8.60a ±0.27	5.61a ±0.04
GC 584	3.79ab ±0.37	1.41bcd ±0.13	0.95a ±0.15	1.49cde ±0.14	2.28b ±0.29	2.20abc ±0.13	5.95a ±0.22	4.08a ±0.11
GC 785	2.64d ±0.35	1.37bcd ±0.09	0.94a ±0.19	1.77bcd ±0.06	1.94b ±0.22	2.82a ±0.09	3.79a ±0.14	3.31a ±0.13
GC 796	3.57abc ±0.85	2.76a ±0.78	0.97a ±0.28	1.10def ±0.07	2.86a ±0.47	-	-	-
GC 940	2.73d ±0.46	1.77bcd ±0.53	0.75a ±0.19	1.84bcd ±0.14	1.79b ±0.18	0.86abc ±0.78	5.28a ±0.21	3.07ab ±0.46
GT 529	3.14bcd ±0.29	1.23cd ±0.10	0.62a ±0.08	1.52cde ±0.25	1.92b ±0.43	-	-	-
GU 608	3.96a ±0.77	2.10ab ±0.44	0.80a ±0.13	2.74a ±0.41	3.19a ±0.11	0.75c ±0.53	5.20a ±0.23	2.98b ±0.24
GC 3	-	-	-	-	-	2.33abc ±0.10	6.18a ±0.22	4.26a ±0.08
GC 522	-	-	-	-	-	2.08abc ±0.44	5.70a ±0.21	3.89a ±0.22
GC 746	-	-	-	-	-	2.59ab ±0.11	3.79a ±0.13	3.19ab ±0.21
GC 962	-	-	-	-	-	1.33abc ±0.13	7.57a ±0.12	4.45a ±0.20
GU 125	-	-	-	-	-	2.04abc ±0.17	7.37a ±0.20	4.71a ±0.18
GU 21	-	-	-	-	-	0.89bc ±0.13	7.18a ±0.18	4.04a ±0.13

Values are mean with ±standard error. Mean values in the same column with same following letters do not differ significantly ($p > 0.05$) based on DMRT.

The study results are in agreement with results reported by Brisow *et al.* (2006) and Patil *et al.* (2012) of mean annual Dbh increments of 2.6 cm yr^{-1} for *Eucalyptus pellita* and Eucalypt clones of 8 years. Low Dbh increment for clones at Lushoto site in 2009 could be due to drought in that particular year. Silviculturally, species with diameter increment of >1 cm yr^{-1} are considered as fast growing (Marcar *et al.*, 1995).

The study results also revealed that from 3 to 8 years, there is an increase in Dbh of Eucalypt clones in the study sites. However, GU 608, GC 584 and GC 581 showed an upward trend of Dbh increment at 3 and 8 years of age at Lushoto site. The study results confirm those reported by Kahunyo (2008) for Eucalypt hybrid clones in Kenya and also in agreement with Tanvir *et al.* (2002) who found that the Dbh of Eucalypt species increased rapidly at more or less constant rate from 1 to 8 years and later the increment was very low and somewhat constant up to the 10^{th} year.

Eucalypt clones at Kibaha and Tabora sites achieved highest Dbh growth than clones at Kwamarukanga site. This could have been a result of wide espacement between trees created by human damage through illegal cutting of the standing stock, fire occurrence and death caused by termite attack after establishment. As would be expected, the trees at wider spacing had greater diameters than those of the same age at close spacing resulting from reduced competition for moisture and nutrients (Palik and Pregitzer, 1995).

4.1.1.3 Height growth

Table 18 shows the growth performance of Eucalypt clones at the four sites based on mean height. The results for Eucalypt clones at Lushoto site revealed that clones GU 608, GC 584 and GT 529 achieved significantly higher mean height compared to the rest of Eucalypt clones. At Kwamarukanga site, clones GT 529, GC 14 and GC 10 had relatively higher mean height than the rest of the Eucalypt clones. At Kibaha site, clones GC 584, GC 15 and GU 608 showed satisfactory mean height values compared to GC 581, GC 785 and GC 796. However, at Tabora site, GC 581, GU 125 and GC 10 showed satisfactory values of mean height compared to GC 514, GC 796 and GU 608.

Table 18: Mean height of 8 year old Eucalypt clones from four sites

Treatment	Height (m)			
	Lushoto	Kwamarukanga	Kibaha	Tabora
GC 10	24.39bcd± 0.84	21.97ab± 0.94	18.36bc± 0.42	16.27ab± 0.86
GC 14	24.93bcd±0.70	22.24a±0.91	19.14abc ±0.68	16.15ab±0.71
GC 15	25.94bcd±0.56	21.19ab±1.09	20.76a±0.43	15.63ab ±0.58
GC 167	24.05cd±0.68	19.18bc±0.83	19.53abc±0.53	14.63ab ±0.68
GC 514	26.36bc ±1.16	21.05ab±0.60	18.94abc ±0.73	13.16bc±0.64
GC 581	25.90bcd±0.58	19.72abc±0.67	18.32bc±0.45	17.5a±1.53
GC 584	26.96b ±0.71	20.95ab±0.67	20.88a ±0.52	16.04ab±0.40
GC 785	23.37d±0.73	19.38bc±0.84	17.91c ±0.56	13.83abc±0.75
GC 796	24.04cd±0.75	18.20c±0.80	17.75c±0.83	-
GC 940	25.73bcd±1.21	19.80abc ±0.55	19.50abc±0.43	14.5abc ±0.63
GT 529	27.05b ±1.07	22.43a±0.86	19.43abc±0.86	-
GU 608	30.81a ±0.93	20.03abc±1.11	20.33ab ±0.99	10.83c±1.30
GC 3	-	-	-	15.05ab±0.89
GC 522	-	-	-	13.9abc±0.92
GC 746	-	-	-	13.21bc±0.75
GC 962	-	-	-	16.14ab ±1.01
GU 125	-	-	-	17.5a ±0.32
GU 21	-	-	-	15.4ab±1.13

Values are mean with ±standard error. Values in the same column with same following letters do not differ significantly ($p > 0.05$) based on DMRT.

Height growth of GU 608 at Lushoto site was significantly higher than mean height of 28 m reported by Bernhard-Reversat (2001) for a 7 year old Eucalypt clonal plantation in Congo. Eucalypt clones heights are higher than those reported by Neilan and Thompson (2008) for *Eucalyptus nitens* which reached a height of 11 to 14 m after 8 growing seasons in Coastal Irelands and Kahunyo (2008) who reported mean heights for Eucalypt clones in Kenya ranging between 12.5 m and 19.9 m.

Significant ($p<0.05$) differences in height between clones was observed in each study site. Arya *et al.* (2009) reported that the average height of clones differed significantly within site and these differences between clones may be attributed to genetic differences. The authors further revealed that the difference between clones between sites may be a result of environmental factors like soil type, mean annual rainfall and mean temperature and genetic differences between clones. Height growth, especially in Eucalypts which are shade intolerant is strongly affected by stocking i.e. number of stems per unit area (Varis, 2011). High height growth was observed between clones at Lushoto and Kwamarukanga sites due to high survival rate. However, clones at Kibaha and Tabora sites due to low survival rate resulting into wider spacing with no competition for light, the height growth between clones was observed to be low.

Tables 19 and 20 present the mean annual height increments for Eucalypt clones from four studied sites. Significant difference between clones in MAI for height was observed at Kibaha and Tabora sites. No significant differences in MAI for height between Eucalypt clones were observed at Lushoto and Kwamarukanga sites. Table 19 indicates that GU 608 and GC 15 had the highest MAI for height than the other clones at Lushoto site. In 2007, the site had the highest height increment of 4.98 m yr^{-1} and 4.3 m yr^{-1} while in 2012 the site attained the highest height increment of 11.51 m yr^{-1} and 8.4 m yr^{-1}. At Kwamarukanga site, GT 529 and GC 10 had the highest MAI than the other clones. Maximum height increment of 6.28 m yr^{-1} and 6.26 m yr^{-1} was obtained in 2007 while in 2009 maximum height increment of 5.76 m yr^{-1} and 5.24 m yr^{-1} was achieved at this site. At Kibaha site, MAI for height was higher for GC 584, GC 15 and GC 796 and lowest

MAI achieved by CG 167. MAI for height was higher for GC 15 and GC 514 with the lowest recorded for GC 746 in 2007. For Tabora site, GC 581 and GC 962 recorded significantly higher MAI for height than the other clones. The site showed highest height increment of 9.49 m $yr^{-1}$and 8.80 m yr^{-1} and the lowest was GC 785 in 2012.

Table 19: Periodic height increment of Eucalypt clones at Lushoto and Kwamrukanga sites

Treatment	Lushoto site				Kwamarukanga site				
	Height increment			MAI	Height increment				MAI
	2008	2009	2012	(m yr^{-1})	2007	2008	2009	2012	(m yr^{-1})
GC 10	3.60ab ±0.99	0.21b ±0.82	6.94bcd ±0.29	3.58ab ±0.55	6.07a ±0.76	0.21c ±0.35	4.46abc ±0.65	4.07a ±0.30	3.70a ±0.44
GC 14	3.78ab ±1.11	0.45ab ±0.76	6.77bcd ±0.41	3.67ab ±0.42	4.87bc ±0.34	0.67ab ± ±0.16	4.06bc ±0.42	3.73a ±0.50	3.33ab ±0.40
GC 15	4.20ab ±1.01	1.00ab ± 1.13	6.79bcd ±0.24	4.00ab ±0.71	4.33ab ±0.17	1.21ab ±1.07	5.24ab ±0.18	1.62ab ±0.47	3.35ab ±0.26
GC 167	4.98a ±1.08	0.44ab ±0.59	5.26cd ±0.17	3.56ab ±0.41	6.26a ±0.23	0.11c ±0.67	4.45abc ±0.32	1.11ab ±0.13	2.98ab ±0.25
GC 514	2.97ab ±1.30	0.01b ±0.16	7.55bc ±0.24	3.51ab ±0.20	5.79ab ±0.56	0.79ab ±0.29	4.71abc ±0.59	2.39ab ±0.42	3.42ab ±0.49
GC 581	4.30ab ±0.81	0.15b ±1.26	7.19bcd ±0.26	3.88ab ±0.81	5.04b ±0.43	1.12ab ±0.52	3.34c ±0.46	1.85ab ±0.17	2.84ab ±0.39
GC 584	3.13ab ±1.03	1.48a ±0.82	7.22bcd ±0.29	3.94a ±0.59	5.74ab ±0.45	1.12ab ±1.04	5.15ab ±0.50	1.68ab ±0.42	3.42ab ±0.26
GC 785	4.30ab ±1.20	0.01b ±0.89	4.50d ±0.36	2.94ab ±0.57	4.29c ±0.72	0.87ab ±0.52	4.63abc ±0.62	2.70a ±0.35	3.12ab ±0.58
GC 796	3.10ab ±1.01	0.66ab ±0.87	4.80cd ±0.26	2.85ab ±0.69	5.02b ±0.68	0.12c ±0.95	4.35abc ±0.22	1.07ab ±0.24	2.64ab ±0.29
GC 940	3.09ab ±0.94	0.01b ±0.12	8.41b ±0.10	3.84ab ±0.10	5.97a ±0.47	0.75ab ±0.88	5.76a ±0.68	0.66b ±0.43	3.29ab ±0.42
GT 529	2.32b ±1.38	0.02b ±0.39	8.06b ±0.43	3.47ab ±0.30	6.28a ±0.64	1.65a ±0.93	5.16ab ±0.73	2.00ab ±0.32	3.77a ±0.50
GU 608	2.56ab ±0.83	0.02b ±0.51	11.51a ±0.23	4.70a ±0.43	5.44ab ±0.28	1.71a ±0.71	4.24bc ±0.25	1.17ab ±0.82	3.14ab ±0.52

Values are mean with ±standard error. Mean values in the same column with same following letters do not differ significantly ($p > 0.05$) based on DMRT.

Table 20: Periodic height increment of Eucalypt clones at Kibaha and Tabora sites

Treatment	Kibaha site Height increments 2007	2008	2009	2012	MAI (m yr^{-1})	Tabora site Height increment 2008	2012	MAI (m yr^{-1})
GC 10	5.32abc ±0.40	1.30de ±0.36	1.08a ±0.11	0.01bcd ±0.29	1.93bc ±0.20	2.54bcd ±0.36	7.23abc ±0.45	4.89ab ±0.36
GC 14	5.99ab ±0.27	0.99e ±0.19	1.12a ±0.23	0.04bcd ±0.22	2.04b ±0.25	3.32abc ±0.19	7.01abc ±0.34	5.17ab ±0.19
GC 15	6.99a ±0.23	1.20de ±0.22	1.31a ±0.17	0.85ab ±0.04	2.59a ±0.18	2.64bcd ±0.22	7.78abc ±0.37	5.21ab ±0.22
GC 167	5.03abc ±1.26	1.09e ±0.25	1.43a ±0.30	0.04bcd ±0.32	1.90bc ±0.12	2.91bcd ±0.25	6.49abc ±0.23	4.70ab ±0.25
GC 514	6.72a ±0.23	1.59cde ±0.52	0.60a ±0.65	0.05bcd ±0.51	2.24ab ±0.12	2.17cde ±0.52	7.67abc ±0.41	4.92ab ±0.52
GC 581	4.32bc ±1.86	2.7b ±1.34	1.52a ±0.13	0.05bcd ±0.27	2.15b ±0.70	4.02a ±1.34	8.80ab ±0.39	6.41a ±1.34
GC 584	6.63a ±0.43	1.22de ±0.26	1.28a ±0.22	1.34a ±0.36	2.62a ±0.45	2.57bcd ±0.26	7.77ab ±0.28	5.17ab ±0.26
GC 785	6.44a ±0.28	1.21de ±0.27	1.13a ±0.06	0.04bcd ±0.28	2.21ab ±0.15	3.4ab ±0.27	4.39c ±0.19	3.90abc ±0.27
GC 796	3.55c ±0.78	5.23a ±1.11	1.22a ±0.55	0.10abcd ±0.15	2.53a ±0.82	-	-	-
GC 940	5.20abc ±0.61	2.13bcd ±0.70	1.39a ±0.10	0.13abc ±0.32	2.21ab ±0.20	2.90bcd ±1.11	5.06bc ±0.18	3.98abc ±1.11
GT 529	5.29abc ±0.47	2.31bc ±0.12	1.02a ±0.32	0.04bcd ±0.70	2.17b ±0.56	-	-	-
GU 608	6.22ab ±0.76	1.91bcde ±0.51	1.13a ±0.05	0.34abc ±0.67	2.40ab ±0.50	1.25e ±0.70	6.50abc ±0.12	3.88abc ±0.12
GC 3	-	-	-	-	-	2.96bcd ±0.12	7.30abc ±0.62	5.13ab ±0.51
GC 522	-	-	-	-	-	2.88bcd ±0.51	6.93abc ±0.32	4.91ab ±0.32
GC 746	-	-	-	-	-	2.56bcd ±0.61	6.92abc ±0.43	4.74ab ±0.22
GC 962	-	-	-	-	-	2.15bd ±0.21	9.49a ±0.67	5.82a ±0.34
GU 125	-	-	-	-	-	2.08de ±0.34	8.67ab ±0.56	5.38ab ±0.12
GU 21	-	-	-	-	-	1.90de ±0.23	7.33abc ±0.72	4.62ab ±0.33

Values are mean with ±standard error. Mean values in the same column with same following letters do not differ significantly ($p > 0.05$) based on DMRT.

All Eucalypt clones showed high height growth rate during the first 3 years. Similar results have been documented by Tanvir *et al.* (2002) in India who found that height of the trees increased rapidly for the first 4 years and later on, the height increment increased slowly showing comparatively slow growth. GU 608 showed an upward height increment trend and maintained its superiority at the age of 2, 3, 4 and 8 years. These results are in agreement with results of Neilan and Thompson (2008) and Patil *et al.* (2012) which showed that Eucalypt clones recorded significantly higher height compared to other *Eucalyptus* species in India but lower than the results from this study. The difference in performance among clones at various sites is an indication that some clones are more adaptable to specific sites (Kirongo and Muchiri, 2009).

MAI for height was significantly higher for GU 608 and GC 15 compared to the other clones, showing that they are better adapted to this environment than the others. Kahunyo (2008) and Oballa *et al.* (2009) reported that Eucalypt clones had significant higher MAI for height of over 2 m in Kenya, 3.4 m y^{-1} for *E. grandis* for 5.5 years old in South Australia and 1.4 m yr^{-1} to 2.4 m yr^{-1} for *E. grandis* for 4.5 years in Northern Victoria. The best clone at Lushoto site had about 2 times more height than the best clones at the other sites, implying that they are favoured by environmental and ecological factors. In addition, closely growing trees are known to have faster initial height growth than widely growing trees. In Lushoto due to excellent survival trees were closely packed which could have influenced competitive height growth.

4.1.1.4 Basal area

The basal area of Eucalypt clones from the study sites is presented in Tables 21 and 22. Significant ($p<0.05$) difference in basal area between Eucalypt clones within a site in all studied sites were observed (Tables 21 and 22). GC 581, GC 584 and GU 608 showed superior value for basal area of clones at Lushoto site. At Kwamarukanga site, GT 529, GC 940 and GC 514 showed satisfactory value of basal area while GU 608, GC 10 and GC 14 recorded lowest basal area (Table 21). Kibaha site showed significant higher basal area for GC 167, GC 15 and GC 940 when compared to the other clones (Table 22). However, at Tabora site, clones GC 962, GC 584 and GC 940 outperformed the other clones (Table 22).

Table 21: Basal area of 8 year old Eucalypt clones for Lushoto and Kwamarukanga sites

Treatment	Basal area (m^2 ha^{-1})								
	Lushoto site				Kwamarukanga site				
	2007	2008	2009	2012	2006	2007	2008	2009	2012
GC 10	10.62f	13.80e	13.97f	19.21e	2.37g	6.42d	6.33f	6.42f	3.97g
GC 14	10.29g	13.47f	14.33e	18.29f	2.45fg	5.66f	6.60e	6.71f	4.62f
GC 15	12.02d	15.49c	15.56c	21.02d	3.07c	7.68a	8.79b	10.23b	11.69b
GC 167	12.42b	16.19b	16.68a	21.24cd	3.08c	7.05c	7.30d	8.54d	10.14c
GC 514	9.99h	12.13g	12.13i	17.20g	3.31b	7.14bc	8.60b	10.14b	12.77a
GC 581	12.41b	16.62a	16.64a	21.76bc	3.05c	6.51d	7.41d	8.48d	9.34d
GC 584	12.26bc	16.33ab	16.29b	21.94b	2.92d	6.72d	7.82c	9.64c	11.74b
GC 785	11.08e	14.78d	15.00d	18.07f	3.01c	6.08e	6.69e	7.96e	9.54d
GC 796	12.07cd	15.57c	15.40c	18.49f	2.52f	5.13g	5.49g	6.15f	6.53e
GC 940	10.75f	13.34f	13.34g	18.06f	3.23b	7.40b	8.75b	10.22b	12.70a
GT 529	10.22g	12.37g	12.56h	16.88gf	3.49a	7.86a	9.12a	11.73a	12.66a
GU 608	12.96a	16.26b	16.42ab	28.18a	2.79d	3.29h	2.65h	3.26g	3.88g

Mean values in the same column with same following letters do not differ significantly ($p> 0.05$) based on DMRT.

Table 22: Basal area of 8 year old Eucalypt clones for Kibaha and Tabora sites

Treatment	Basal area (m^2 ha^{-1})							
	Kibaha site					Tabora site		
	2006	2007	2008	2009	2012	2007	2008	2012
GC 10	3.02e	6.17d	5.87e	5.85e	4.16e	1.77de	2.16f	5.67cd
GC 14	2.34g	5.57e	4.38f	3.90g	4.16e	1.54e	3.69cd	6.13cd
GC 15	3.70b	8.91a	10.69a	12.40a	14.61a	3.32a	5.82a	6.64cd
GC 167	3.16de	7.29c	8.67c	9.66b	11.44b	2.84ab	4.62b	5.84cd
GC 514	3.21cde	7.18c	8.66c	8.73c	10.69b	1.71de	2.89def	4.61de
GC 581	2.62f	5.49e	6.20de	6.32e	5.04e	3.00a	5.47a	2.78ef
GC 584	3.35cd	8.50ab	9.28b	10.10b	11.16b	1.83de	3.37de	10.00ab
GC 785	3.12de	6.19d	6.66d	6.30e	6.42d	1.51e	2.59ef	3.09ef
GC 796	1.14h	4.90f	3.16g	3.77g	4.18e	-	-	-
GC 940	4.36a	8.06b	10.70a	11.96a	14.61a	3.28a	6.06a	10.51a
GT 529	3.45bc	7.13c	8.23c	7.63d	9.54c	-	-	-
GU 608	2.26g	5.45e	4.29f	4.81f	6.67d	1.74de	2.12f	0.78f
GC 3	-	-	-	-	-	1.65de	3.36de	2.34f
GC 522	-	-	-	-	-	1.39ef	2.89def	1.76f
GC 746	-	-	-	-	-	1.81de	4.18bc	2.39f
GC 962	-	-	-	-	-	2.42bc	3.37de	7.96bc
GU 125	-	-	-	-	-	1.00f	2.34f	1.13f
GU 21	-	-	-	-	-	2.10bc	3.44cd	7.23c

Mean values in the same column with same following letters do not differ significantly ($p > 0.05$) based on DMRT.

The results also revealed that there were increasing trends of basal area in all sites from 3 to 5 years and thereafter, a decreasing trend in some sites. The decrease in basal area in some years at Tabora site was probably influenced by illegal tree cutting for poles and the effect of site matching where some clones are suitable in specific areas as reported by Wamalwa *et al.* (2007). The GC clones are more suited for growing in medium agricultural potential areas receiving annual rainfall of above 750 mm and at an elevation of less than 1700 m.a.s.l (Oballa *et al.,* 2009). The GCs are not suitable for growing in semi-arid areas where *E. camaldulensis* does best or above 1700 m.a.s.l. where *E. grandis* grows best. Wamalwa *et al.* (2007) found that in high rainfall areas with amounts over 1200 mm a year, the growth rate of GCs is lower than that of widely grown local *E. grandis.* Delgado-Mutas and Pukkala (2011) reported that *E. resinifera* grew 25 m^2 ha^{-1} in Tchianga with 15 year rotation length similar to Lushoto but higher than results from Kwamarukanga, Kibaha and Tabora sites. Bernhard-Reversat (2001) in Congo reported that Eucalypt clonal plantation of 8 years had a basal area of 16 m^2 ha^{-1}

which is lower than results from Lushoto and higher than the other studied sites. The study results for clones at Kibaha, Kwamarukanga and Tabora sites are lower than 15.1 m^2 ha^{-1} reported by Rossi *et al.* (2003) for various Eucalypt clones of 6 years in Brazil.

4.1.1.5 Volume production

Tables 23 and 24 shows mean volume production of Eucalypt clones at Lushoto, Kwamarukanga, Kibaha and Tabora sites. The results revealed that the volume differed significantly ($p<0.05$) between Eucalypt clones in all sites. At Lushoto site, GU 608 recorded significantly higher mean volume followed by GC 584 and GC 581 while GT 529 recorded the lowest volume than other clones (Table 23). At Kwamarukanga site, GC 514, GC 940 and GT 529 showed superior volume while the lowest volume was recorded for GU 608 (Table 23). At Kibaha site, GC 15, GC 940 and GC 167 showed higher volume with the lowest recorded for GC 10 (Table 24). At Tabora site, GC 940, GC 584 and GC 962 showed the highest volume and the lowest was recorded for GU 608 (Table 24). The results further revealed that there was increasing trend of volume production from 2006 to 2009 for all sites and suddenly decreasing in 2012 except for clones at Lushoto site.

Tables 23 and 24 present MAI for volume production. The highest MAI 41.10 m^3ha^{-1} yr^{-1} for volume was found in GU 608 and lowest of 19.13 $m^3ha^{-1}yr^{-1}$ for GT 529 at Lushoto site (Table 23). At Kwamarukanga site, MAI for volume was recorded ranging from 3.41 $m^3ha^{-1}yr^{-1}$ to 21.34 $m^3ha^{-1}yr^{-1}$ for GU 608 and GT 529 respectively (Table 23) while at Kibaha site, MAI for volume was recorded ranging from 3.32 $m^3ha^{-1}yr^{-1}$ to 17.47 $m^3ha^{-1}yr^{-1}$ for GC 14 and GC 15 respectively (Table 24). However at Tabora site, MAI for volume was recorded ranging from 0.31 $m^3ha^{-1}yr^{-1}$ to 13.76 $m^3ha^{-1}yr^{-1}$ for GU 608 and GC 940 respectively (Table 24).

Table 23: Volume production and MAI of Eucalypt clones at Lushoto and Kwamarukanga sites

Treatment	Volume (m^3 ha^{-1})				MAI	Volume (m^3 ha^{-1})					MAI
	Lushoto site					Kwamarukanga site					
	2007	2008	2009	2012	($m^3ha^{-1}yr^{-1}$)	2006	2007	2008	2009	2012	($m^3ha^{-1}yr^{-1}$)
GC 10	116.14f±3.38	160.31e±7.80	161.81f±5.83	239.99d±14.57	25.65d±2.07	21.71g±1.36	60.96±4.23	60.11f±3.78	61.30f±3.96	38.22g±8.11	7.59g±1.20
GC 14	111.75g±3.11	155.30f±6.54	166.91e±10.48	225.67e±12.11	26.2cd±2.88	22.71gf±1.29	53.55f±5.86	62.70e±2.74	60.47f±5.34	44.64f±1.97	7.92g±0.78
GC 15	134.19d±3.33	182.14c±5.77	182.94c±3.93	262.88c±11.71	26.91c±1.33	28.35c±1.12	75.36a±6.40	84.44b±1.57	98.92b±3.89	113.7b±6.26	19.1bc±1.12
GC 167	139.82b±5.21	193.5b±8.70	199.54a±6.57	269.3bc±11.54	29.20b±1.69	28.41c±2.05	67.14c±1.92	69.59d±2.40	81.95d±3.10	98.05c±4.56	15.0d±0.71
GC 514	111.33g±7.48	140.8g±8.30	140.77i±8.28	215.73fg±15.83	19.81g±1.56	30.53b±0.94	67.8bc±5.31	82.37b±1.85	97.78b±3.58	124.3a±5.44	19.5b±0.85
GC 581	139.46b±3.18	198.57a±5.79	198.96a±4.87	274.94b±17.29	29.89b±2.21	28.15c±0.64	61.92d±3.69	70.78d±0.42	81.51d±1.47	90.26d±2.49	14.22e±0.51
GC 584	137.7bc±4.19	193.6b±6.56	194.13b±5.90	277.16b±8.82	29.78b±1.26	26.82d±0.72	63.69d±4.79	74.67c±1.13	92.79c±3.21	114.3b±5.01	18.61c±0.91
GC 785	122.35e±2.54	175.2d±5.75	173.81d±4.47	222.40ef±11.17	24.11e±1.62	27.80c±1.99	57.96e±5.05	63.65e±3.95	76.35e±5.25	92.21d±7.83	13.72e±1.31
GC 796	135.4cd±7.20	182.37c±11.47	185.99c±11.57	230.60e±19.16	22.07f±2.71	23.07f±0.72	48.26g±0.46	52.01g±2.55	58.77f±3.95	62.83e±5.87	9.33f±1.01
GC 940	120.44e±6.52	156.18f±7.71	156.22g±7.72	225.86e±7.18	21.21f±0.62	29.75b±1.66	70.38b±6.53	83.76b±5.69	98.51b±7.57	123.4a±10.47	19.7b±1.95
GT 529	113.66fg±6.52	143.6g±8.46	145.73h±10.08	209.23g±11.02	19.13g±4.06	32.26a±1.34	75.09a±7.51	87.54a±3.19	114a±9.79	123.2a±9.58	21.34a±1.67
GU 608	150.83a±7.49	198.21a±9.16	200.06a±8.99	385.23a±24.68	41.10a±3.29	25.75e±2.01	31.28h±6.97	25.47h±9.41	31.61g±11.43	37.81g±13.67	3.41h±1.68

Values are mean with ±standard error. Mean values in the same column with same following letters do not differ significantly ($p > 0.05$) based on DMRT.

Table 24: Volume production and MAI of Eucalypt clones at Kibaha and Tabora sites

Treatment	Kibaha					MAI	Tabora			MAI
	2006	2007	2008	2009	2012	($m^3ha^{-1}yr^{-1}$)	2007	2008	2012	($m^3ha^{-1}yr^{-1}$)
GC 10	17.63e±1.74	38.84d±3.97	38.08e±5.60	38.56e±7.36	28.07e±6.46	4.18f±1.62	14.10cd±3.97	16.70f±5.60	39.88bc±6.46	6.31ab±0.95
GC 14	13.25g±0.98	34.664±1.99	27.82f±1.72	25.2g±2.25	28.57e±19.35	3.32f±1.80	12.12d±1.99	27.76cd±1.72	43.29bc±19.35	9.95ab±2.44
GC 15	22.06b±3.13	58.06a±4.64	71.44a±5.81	84.36a±7.46	103.29a±13.42	17.47a±2.05	25.71a±4.64	43.54a±5.81	46.82bc±13.42	8.77ab±1.95
GC 167	18.65de±2.57	46.9c±4.50	57.46c±5.58	65.28b±6.39	80.92b±5.84	13.22c±1.26	22.18a±4.50	35.01b±5.58	41.13bc±5.84	6.81ab±1.05
GC 514	18.93cde±2.77	46.71c±4.24	57.08c±4.56	58.74c±1.04	74.87b±10.70	12.14c±1.32	13.52cd±4.24	21.84def±4.56	33.01cd±10.70	5.67ab±1.95
GC 581	15.36f±1.65	34.70d±2.98	40.70de±1.07	42.55e±7.47	34.99e±11.46	6.04e±2.09	23.23a±2.98	40.75a±1.07	18.78def±11.46	8.14ab±0.89
GC 584	19.85cd±1.82	55.37ab±7.31	61.86b±3.72	68.78b±4.95	78.47b±12.41	13.19c±1.55	14.74bcd±7.31	25.86cd±3.72	70.88a±12.41	10.98ab±1.97
GC 785	18.27de±1.09	39.12d±2.17	43.23d±4.82	41.73e±8.41	44.27d±8.17	6.12e±1.97	12.25d±2.17	19.98fe±4.82	22.30de±8.17	5.66ab±1.66
GC 796	6.52h±1.51	32.12e±10.77	21.57g±6.95	26.28g±7.38	30.25e±10.37	5.34e±1.76	-	-	-	-
GC 940	26.55a±6.34	52.37b±10.66	71.62a±14.97	81.09a±16.00	102.01a±21.11	15.73b±3.03	25.51a±10.77	45.08a±6.95	73.42a±10.37	13.76a±1.91
GT 529	20.56bc±3.83	45.87c±7.31	54.12c±13.44	50.92d±11.67	65.24c±11.56	9.02d±1.95	-	-	-	-
GU 608	13.49g±4.58	35.42de±11.37	28.87f±8.82	32.73f±9.74	45.12d±11.85	6.25e±1.50	13.87cd±10.66	16.44f±14.97	5.69f±21.11	0.31b±3.93
GC 3	-	-	-	-	-	-	13.23cd±7.31	25.69cde±13.44	16.46ef±11.56	5.09ab±3.01
GC 522	-	-	-	-	-	-	11.15de±6.34	22.13def±8.82	12.69ef±1.13	8.47ab±0.88
GC 746	-	-	-	-	-	-	14.10cd±11.37	31.11bc±3.21	17.23ef±2.56	11.33a±2.90
GC 962	-	-	-	-	-	-	18.38b±2.78	25.19cde±8.23	55.24b±11.85	7.21ab±1.87
GU 125	-	-	-	-	-	-	7.93e±1.19	17.68f±3.33	7.92ef±1.01	9.25ab±3.11
GU 21	-	-	-	-	-	-	16.58bc±2.91	26.11cd±.4.51	49.51b±6.32	8.77ab±1.78

Values are mean with ±standard error. Mean values in the same column with same following letters do not differ significantly ($p > 0.05$) based on DMRT.

The productivity falls in the range reported for some Eucalypt hybrid plantations (*E. urophylla* × *E. grandis*) in South Africa, South America and India with MAI ranging from 15 - 60 $m^3ha^{-1}yr^{-1}$ (Luna *et al.,* 2009; Almeida *et al.,* 2010; Pérez-Sandoval *et al.,* 2012), 25 – 89.5 $m^3ha^{-1}yr^{-1}$ in Brazil and Cameron (Eldridge *et al.,* 1993). The MAI presented in Tables 23 and 24 are lower than those found by similar studies on *Eucalyptus nitens* in Chile ranging from 47 to 52 $m^3ha^{-1}yr^{-1}$ (Rodríguez *et al.,* 2009) and 50 $m^3ha^{-1}yr^{-1}$ for *E. saligna*, and more than 60 $m^3ha^{-1}yr^{-1}$ for some *E. grandis* provenances and hybrids under intensive management practices, genetic improvement and high productivity sites (Staple *et al.,* 2010).

However in Brazil, intensive breeding has resulted in MAI of between 33 $m^3ha^{-1}yr^{-1}$ and 70 $m^3ha^{-1}yr^{-1}$ for *E. grandis* and *E. urophylla* (Parveen *et al.,* 2010). Delgado-Mutas and Pukkala (2011) reported the highest MAI of 37 $m^3ha^{-1}yr^{-1}$ for *E. saligna* in Angola, 35 $m^3ha^{-1}yr^{-1}$ for *E. grandis* and *E. saligna* of 13 years when planted outside Australia and 37.5 $m^3ha^{-1}yr^{-1}$ for *E. grandis x E. urophylla* of 5.7 years in Brazil. Similar observations were also reported by Eldridge *et al.* (1993) and Hunde *et al.* (2002) that MAI of *E. grandis* ranged between 25 $m^3ha^{-1}yr^{-1}$ in Zambia, 41 $m^3ha^{-1}yr^{-1}$ in Taree, exceeding the MAI of 25 $m^3ha^{-1}yr^{-1}$ reported on best sites.

Clones at Lushoto site showed superior volumes than clones at the other sites. This might be attributed to sites advantages in good growth in diameter and height at the study site. Good performance of the Eucalypt clones at Lushoto site might be ascribed to the favourable climatic conditions, especially the high rainfall and soil type. This implies that Eucalypt clones are better adapted to altitudes ranging from 1393 – 1486 m.a.s.l with rainfall above 1000 mm and temperature ranging between 7^0C and 30^0C.

The growth of trees is mainly influenced by different factors including genotype, environment and management. The differences in performance among Eucalypt clones at various sites indicate that some clones are more adaptable to specific sites (Kirongo and Muchiri, 2009; Wamalwa *et al.,* 2007). According to Arya *et al.* (2009) different sites have different level of fertility, soil texture etc. It was evident that clones at Lushoto performed better, showing the influence of environment on tree growth. However, GU 608 performed well at Lushoto site only, implying that they are not suitable in low land and dry areas. Similar observations have been made by Hardiyanto (1996) that GUs was not suitable for lowland humid tropics.

However, the four study sites varied greatly in productivity, for reasons that could include: varying rainfall, nutrient availability or evapotranspiration among the sites. Growth rate and productivity of Eucalypts may also vary from country to country and even within a country of varying site qualities and from one stand to another (Eldridge *et al.,* 1993; Marcar and Crawford, 2004). Piketty *et al.* (2008) reported that the productivity of Eucalypt clones is determined by water availability (precipitation and irrigation), genetic material, species behaviour, fertilization, temperature, altitude, soil characteristics and management practices. These hybrids have the potential to make the marginal areas more productive by combining the fast growth trait of *E. grandis* and the drought resistance and better wood quality traits of *E. tereticolnis* and *E. camaldulensis* (Gwaze *et al.,* 2000). Eucalypt clones provide excellent performance with annual growth rate of which due to the increasing wood demand of the national timber and poles market, made some private farmers also plant Eucalypts.

4.1.1.6 Biomass production

Tables 25 and 26 present biomass production of Eucalypt clones growing at the four studied sites. Significant variation in biomass production between clones was observed for biomass production. Lushoto site, in particular, differed from the other sites in terms of having high biomass production. The results revealed that Lushoto site has biomass production ranging from 147.87 t ha^{-1} to 286.85 t ha^{-1} with maximum biomass production attained by GU 608 and minimum by GT 529 (Table 25). Kwamarukanga site recorded biomass production ranging from 27.33 t ha^{-1} to 89.92 t ha^{-1} for GU 608 and GC 514 respectively (Table 25). At Kibaha site, biomass production ranged from 22.30 t ha^{-1} to 86.35 t ha^{-1} for GU 608 and GC 15 respectively (Table 26). However, clones at Tabora site recorded biomass production ranging from 4.66 t ha^{-1} to 58.82 t ha^{-1} for GU 608 and GC 940 respectively (Table 26).

Table 25: Biomass production of Eucalypt clones at Lushoto and Kwamarukanga sites

	Biomass (t ha^{-1})								
Treatment	**Lushoto**				**Kwamarukanga**				
	2007	**2008**	**2009**	**2012**	**2006**	**2007**	**2008**	**2009**	**2012**
GC 10	76.77f	109.52f	110.31f	170.56d	15.21g	43.49d	42.90f	43.84f	27.45g
GC 14	73.57h	105.64g	114.13e	159.23efg	15.75fg	38.15f	44.78e	43.34f	32.12f
GC 15	89.62d	125.08d	125.61c	186.58c	19.45c	52.49a	60.60b	71.21b	82.09b
GC 167	98.85b	134.21b	138.38a	192.75b	19.98c	47.98c	49.76d	58.79d	70.59c
GC 514	74.38gh	96.06h	96.10i	153.60gh	21.49b	48.44bc	59.03b	70.31b	89.76a
GC 581	93.50b	137.55a	137.46a	196.29b	19.80c	44.21d	50.66d	58.50d	64.95d
GC 584	92.23bc	134.08b	133.70b	197.77b	18.84d	45.42d	53.41c	66.64c	82.20b
GC 785	81.31e	119.52d	121.06d	156.84fg	19.56c	41.14e	45.71e	54.74e	66.35d
GC 796	90.81cd	129.06c	125.89c	163.92e	16.18f	34.29g	37.08g	42.06f	45.11e
GC 940	80.71e	107.17fg	107.19g	160.64ef	20.92b	50.27b	60.01b	70.79b	89.07a
GT 529	75.85fg	98.02h	99.49h	147.87h	22.73a	53.73a	60.80a	82.19a	89.92a
GU 608	103.04a	138.79a	140.03a	286.85a	18.11e	22.31h	18.28h	22.78g	27.33g

Values in the same column with same following letters do not differ significantly ($p > 0.05$) based on DMRT.

Table 26: Biomass production of Eucalypt clones at Kibaha and Tabora sites

Treatment	Biomass (t ha^{-1})							
	Kibaha					Tabora		
	2006	2007	2008	2009	2012	2007	2008	2012
GC 10	11.97e	28.52d	29.01e	29.88f	22.30e	11.99cd	14.01g	32.07bc
GC 14	8.71g	25.19e	20.66f	19.11h	23.16e	10.27d	23.12cd	34.88bc
GC 15	15.34b	44.44a	56.18a	67.63a	86.35a	21.58a	35.97a	37.67bc
GC 167	12.79de	35.37c	44.80c	51.97b	67.74b	18.71a	29.10a	33.09bc
GC 514	13.01de	34.64c	44.19c	46.49c	61.94b	11.47cd	18.15efg	26.74cd
GC 581	10.47f	25.66e	31.38de	33.79e	28.70e	19.51a	33.60a	14.82ef
GC 584	13.68cd	42.38ab	48.18b	55.06b	65.22b	12.58bcd	21.62cde	57.16a
GC 785	12.44de	28.95d	32.92d	32.50ef	36.01d	10.52d	25.65bc	18.13de
GC 796	4.35h	25.39e	17.39g	21.68h	25.98e	-	-	-
GC 940	18.84a	39.91b	56.34a	64.75a	84.12a	21.46a	37.30a	58.82a
GT 529	14.27bc	34.58c	41.80c	39.93d	52.57c	-	-	-
GU 608	9.35fg	27.21de	22.87f	26.26g	39.35d	11.81cd	13.81g	4.66f
GC 3	-	-	-	-	-	11.03cd	21.45cde	13.25ef
GC 522	-	-	-	-	-	9.53de	18.89defg	10.31ef
GC 746	-	-	-	-	-	11.88cd	16.74fg	14.01ef
GC 962	-	-	-	-	-	15.32a	20.84def	44.14b
GU 125	-	-	-	-	-	6.75e	14.69g	6.35ef
GU 21	-	-	-	-	-	14.04bc	21.72cde	39.32b

Values in the same column with same following letters do not differ significantly ($p > 0.05$) based on DMRT.

These results compare well with several results presented by Hansen and Baker (1979) and Poggiani and Couto (1983) for fast growing *Eucalyptus* species showing the strong potential of Eucalypts for wood production. According to Safou-Matondo *et al.* (2005) total biomass differed between clones and among *E. grandis* x *E. urophylla* (GU) clones: 108 to 155 t ha^{-1} for GU clones which is lower than Lushoto site but higher than the other studied sites. Closely related results were also reported by Bernhard-Reversat (2001) with biomass production of 100 to 120 t ha^{-1} at 7 years of age for Eucalypt clonal plantations in Congo, Gonçalves and De Barros (1999) reported above ground biomass production of 227 t ha^{-1} for *E. grandis* of 7 years old, 163 t ha^{-1} for *E. grandis* of 10 years old (Silva *et al.,* 1983 in Gonçalves and De Barros, 1999), 82 t ha^{-1} for *E. citriodora* of 9 years old (Reis *et al.,* 1987 in Gonçalves and De Barros, 1999) and 137 t ha^{-1} for *E saligna* of 10 years old (Poggiani, 1985 in Gonçalves and De Barros, 1999).

Results further indicate that Lushoto site showed significant ($p<0.05$) higher biomass production compared to the other sites. However, there was increasing trend of biomass production from one year to another and a good trend was observed at Lushoto site where there was high survival. Tabora site was affected by illegal harvesting of poles, site matching effect and fire which occurred in 2009. Growth differences have been found in many cold tolerant Eucalypt species tested under South African growing conditions (Swain *et al.*, 1998; Swain and Gardner, 2000), signifying the importance of site-species matching, as well as site-provenance matching (Swain and Gardner, 2002; Swain and Gardner, 2003).

Differences between genetic materials of Eucalypts in terms of biomass yield and distribution have been attributed to varying adaptability to local conditions as reported by several authors (Leles *et al.,* 2001; Molica, 1992; Neves, 2000; Schumacher, 1998; Silva *et al.,* 2004 in Andrade *et al.,* 2013). Biomass accumulation is a result of greater or more effective capture of growth inducing resources such as water, nutrients and/or solar radiation.

4.1.1.7 Ordinal ranking of clones

Ranking of treatments based on six parameters (survival, height, Dbh, basal area, volume and biomass production) is as shown in Tables 27 and 28 for all studied sites. Based on the parameters, GC 581, GC 584 and GU 608 showed better performance for Lushoto site. GC 15, GC 167 and GC 940 showed better growth performance at Kibaha site (Table 27). However, GC 514, GT 529 and GC 940 performed better than other Eucalypt clones at Kwamarukanga site. At Tabora site, GU 21, GC 584 and GC 940 scored higher than other clones, but GU 21 was not selected as best performer because the stems were not uniform, had too many branches, and was not straight, therefore GC 15 was selected instead of GU 21. Therefore, it can be concluded that GC 15, GC 584 and GC 940 are initially better clones for Tabora site (Table 28). Ordinal ranking values reported in this study show that, GC 940 grows well in different climatic conditions. This indicates that rainfall, temperature, soil and altitude of the study sites are within the optimal range for the survival and growth of GC 940.

Table 27: Ordinal ranking of tree variables for Eucalypt clones at Lushoto and Kibaha sites

Treatment	Lushoto								Kibaha							
	Parameters and ordinal ranking score						Mean	Overall	Parameters and ordinal ranking score						Mean	Overall
	1	2	3	4	5	6	score	Score	1	2	3	4	5	6	score	score
GC 10	1	7	9	6	6	6	5.8	6	9	12	9	8	9	10	9.5	10
GC 14	2	9	8	8	8	9	7.3	7	7	11	7	9	8	8	8.3	8
GC 15	1	4	5	5	5	5	4.2	4	2	3	2	1	1	1	1.7	**1**
GC 167	1	5	10	4	4	4	4.7	5	6	4	3	3	3	3	3.7	**3**
GC 514	5	6	4	11	11	11	8.0	9	5	5	8	5	5	5	5.5	5
GC 581	2	3	6	3	3	3	3.3	**3**	11	8	10	10	10	9	9.7	11
GC 584	2	2	3	2	2	2	2.2	**2**	4	6	1	4	4	4	3.8	4
GC 785	1	12	12	9	10	10	9.0	11	8	9	11	7	7	6	8.0	7
GC 796	1	11	11	7	7	7	7.3	7	12	1	12	12	12	12	10.2	12
GC 940	3	8	7	10	9	8	7.5	8	1	7	5	2	2	2	3.2	**2**
GT 529	5	10	2	12	12	12	8.8	10	3	10	4	6	6	7	6.0	6
GU 608	6	1	1	1	1	1	1.8	**1**	10	2	6	11	11	11	8.5	9

1=Survival (%); 2=Mean Dbh (cm); 3=Mean height (m); 4=Basal area (m^2 ha^{-1}); 5=Volume (m^3 ha^{-1}) and 6= Biomass production (t ha^{-1}).
Bolded numbers are considered as best performing clones.

Table 28: Ordinal ranking of tree variables for Eucalypt clones at Kwamarukanga and Tabora sites

Treatment	Kwamarukanga								Tabora							
	Parameters and ordinal ranking score						Mean	Overall	Parameters and ordinal ranking score						Mean	Overall
	1	2	3	4	5	6	score	Score	1	2	3	4	5	6	score	score
GC 10	9	9	3	11	10	11	8.8	10	8	7	5	5	5	5	5.8	5
GC 14	8	7	2	10	9	10	7.7	8	5	11	3	6	6	6	6.2	6
GC 15	5	6	4	5	4	5	4.8	5	6	5	6	4	4	4	4.8	**4**
GC 167	3	8	11	6	5	6	6.5	6	11	10	7	8	8	8	8.7	8
GC 514	2	1	5	1	1	1	1.8	**1**	7	14	4	9	9	9	8.7	8
GC 581	6	9	9	8	7	8	7.8	9	12	1	13	12	11	12	10.2	10
GC 584	3	5	6	4	3	4	4.2	4	3	6	2	3	2	2	3.0	**2**
GC 785	4	10	10	7	6	7	7.3	7	10	15	10	11	13	13	12.0	12
GC 796	7	11	12	9	8	9	9.3	12	-	-	-	-	-	-	-	-
GC 940	1	4	8	2	2	3	3.3	**3**	1	4	1	1	1	1	1.5	**1**
GT 529	2	2	1	3	2	2	2.0	**2**	-	-	-	-	-	-	-	-
GU 608	10	3	7	12	11	12	9.2	11	14	16	15	14	15	4	13.0	13
GC 3	-	-	-	-	-	-	-	-	4	8	11	10	12	11	9.3	9
GC 522	-	-	-	-	-	-	-	-	13	12	14	16	14	14	13.8	15
GC 746	-	-	-	-	-	-	-	-	9	13	12	13	10	10	11.2	11
GC 962	-	-	-	-	-	-	-	-	2	9	9	7	7	7	6.8	7
GU 125	-	-	-	-	-	-	-	-	15	3	16	15	16	15	13.3	14
GU 21	-	-	-	-	-	-	-	-	2	2	8	2	3	3	3.3	**3**

1=Survival (%); 2=Mean DBH (cm); 3=Mean Height (m); 4=Basal area (m^2 ha^{-1}); 5=Volume (m^3 ha^{-1}) and 6= Biomass production (t ha^{-1}). Bolded numbers are considered as best performing clones.

Based on the overall growth performance during the first 8 years, the following clones were considered as best s in terms of survival, mean height, mean Dbh, basal area, volume and biomass production parameters in the studied sites. Lushoto - GU 608, GC 584 and GC 581, Kibaha - GC 15, GC 940 and GC 167 (Table 27 in bold), Kwamarukanga - GC 514, GT 529 and GC 940, Tabora - GC 940, GC 584 and GC 15 (Table 28 in bold).

4.2 Water Use by Eucalypt Clones

The mean daily water use of studied Eucalypt clones at Kongowe – Kibaha site is shown in Figures 4 and 6. Results revealed that the average water use for GC 167, GC 15 and GC 940 were 14 L day^{-1}, 7 L day^{-1} and 5 L day^{-1} respectively during wet season (Figure 4). During the measurement period, rainfall totalling 115.9 mm was recorded. During this period, daily minimum and maximum temperatures ranged from 23^0C to 31^0C (Figure 5). Rainfall amounting to 572.2 mm was recorded from 1st April to June 2014 leading to high soil water availability in May and June. During dry season, clones GC 167, GC 15 and GC 940 consumed an average of 11 L day^{-1}, 9 L day^{-1}, and 8 L day^{-1} respectively (Figure 6). Daily minimum and maximum temperatures recorded ranged from 24^0C to 31^0C (Figure 7) and no rainfall was recorded during dry season.

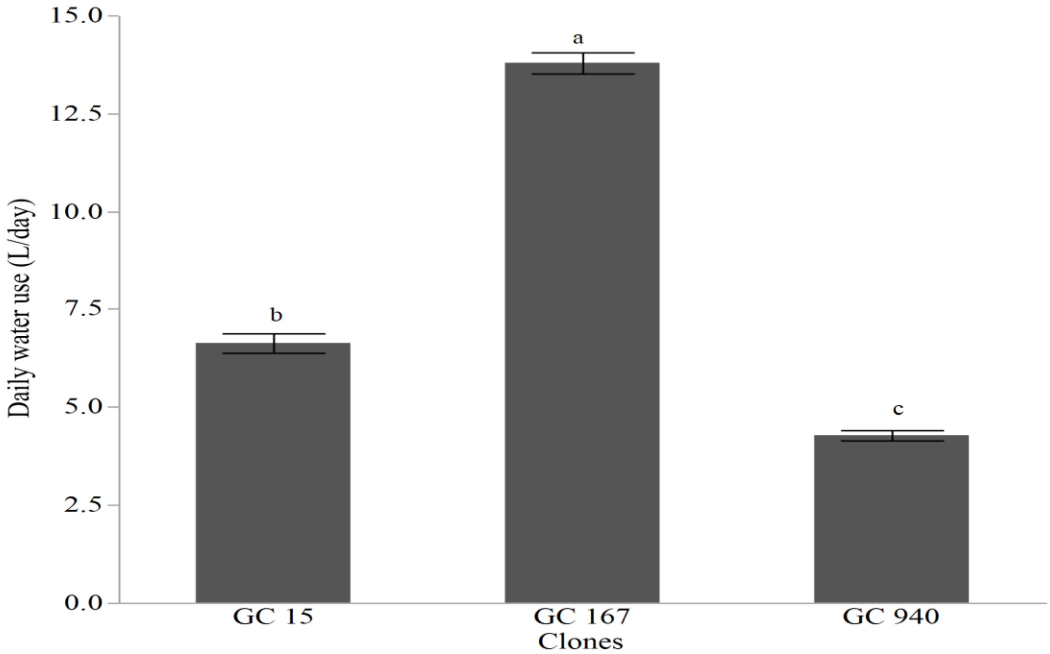

Figure 4: Daily water use of 10 year old Eucalypt clones at Kongowe - Kibaha in wet season

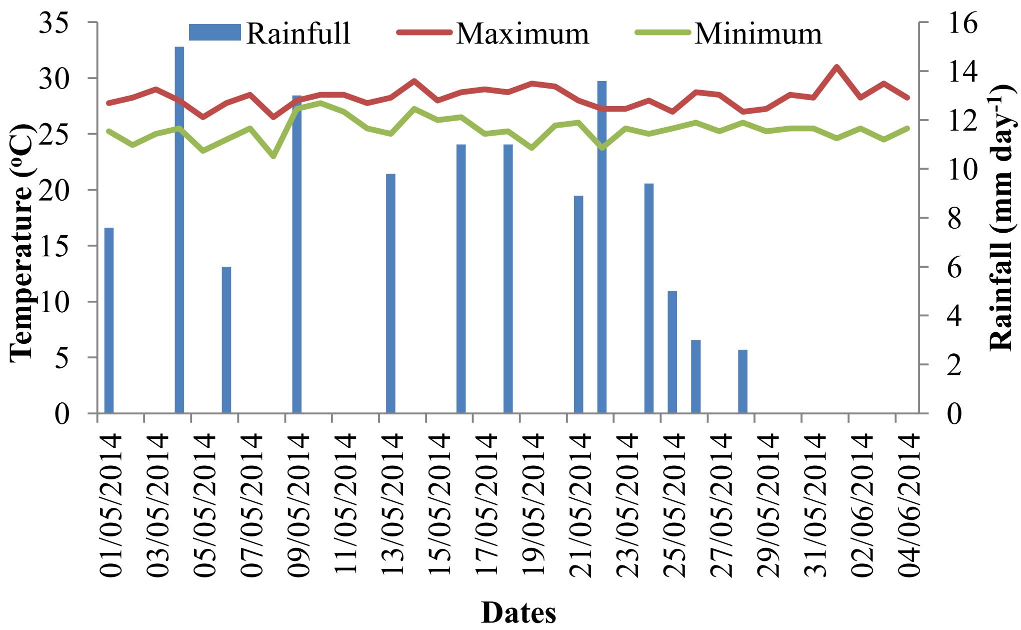

Figure 5: Rainfall and temperature data recorded in wet season at Kongowe - Kibaha, Tanzania.

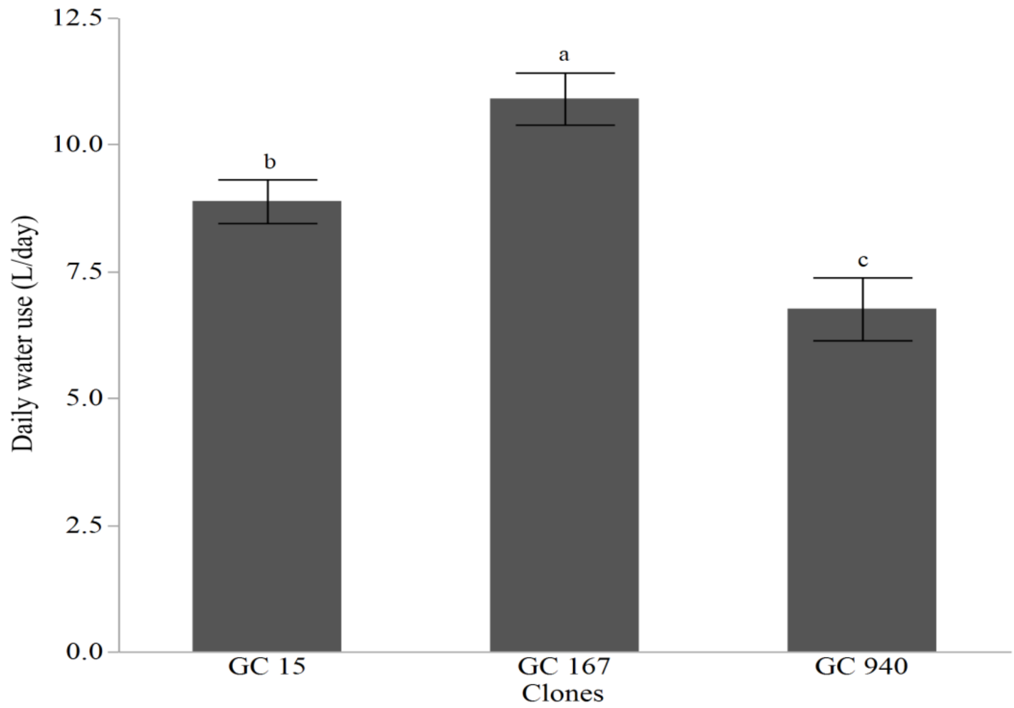

Figure 6: Daily water use of 10 year old Eucalypt clones at Kongowe- Kibaha in dry season

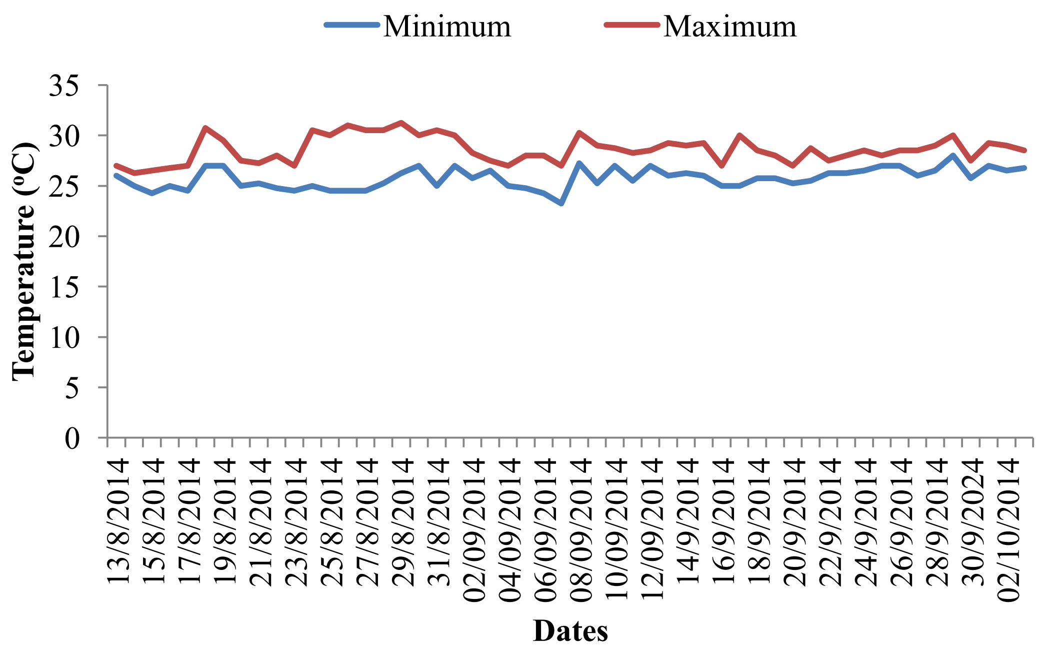

Figure 7: Temperature data recorded in wet season at Kongowe – Kibaha, Tanzania

The average water use results obtained in this study are similar to those reported by Senelwa *et al.* (2009) for Eucalypt clones in Kenya which use about 7 L day^{-1}. Alcorn *et al.* (2013) reported mean water use of 9 L day^{-1} and 11 L day^{-1} for *E. pilularis,* 15 L day^{-1} and 16 L day^{-1} for *E. cloeziana*. The results are lower than those reported by Sunder (1993) and Keitel and Adams (2009) ranging from 20 to 68 L day^{-1} for *E. camaldulensis* and *E. victrix*. Dye *et al*. (2004) reported mean water use in 1.5 – 7 year old stands of *E. grandis* × *camaldulensis* clones ranging from 30 to 64 L day^{-1} for trees growing under high soil water availability, good soil type and high temperature and from 15 to 34 L day^{-1} for sites with poor soil condition.

Results further revealed that GC 167 emerged as the clone with the highest water use than GC 15 and GC 940 though they were of the same age. This was probably a result of larger diameter of the studied tree and the greater sapwood area which transported the larger amounts of water. Simpson (2000) and Keitel and Adams (2009) reported that trees with greater sapwood area and large diameter transported large amount of water than the smallest trees. Alcorn *et al.* (2013) found that smaller sapwood area, crown length and projected crown area of *E. pilularis* resulted in lower water use. A study by Gush (2011) reported that small trees used considerably less water than larger trees of the same species, and this was due to their relatively smaller leaf and sapwood conducting areas. The greater sapwood area would be expected to increase water use by increasing the conductance of the stand as a conduit for water from soil to atmosphere (Morris *et al.,* 2004). The high variation in water use implies that stem diameters determined the actual quantity of water taken up by trees as the transpiration flux and diameter are normally closely related to conducting wood area (Hatton *et al*., 1995). Dye and Olbrich (1993) found that the total functional leaf area on a tree determines the amount of transpiring surface, since very little water is lost directly through the branches and trunks.

Influence of temperature on water use

Temperature has significant ($p<0.05$) correlation with amount of water used by Eucalypt clones (Figure 8). Results revealed that as temperature increases the amount of water used increases with correction coefficient of 0.34. Morris *et al*. (2006) compared single species of *E. camaldulensis* on two sites in Australia and Pakistan. Australia site was established in low temperature zone and Pakistan site was established in high temperature zone. The author found about 3 times more water use by *E. camaldulensis* in Pakistan environments as compared to that in Australia. Calder (1992) reported that changes in water use are determined primarily by changes in climatic demand or by physiological responses to an increase in soil water availability or both. Gush (2011) concluded that seasonal variations in sap velocity are highly correlated to climatic stimuli such as changes in temperature and day length.

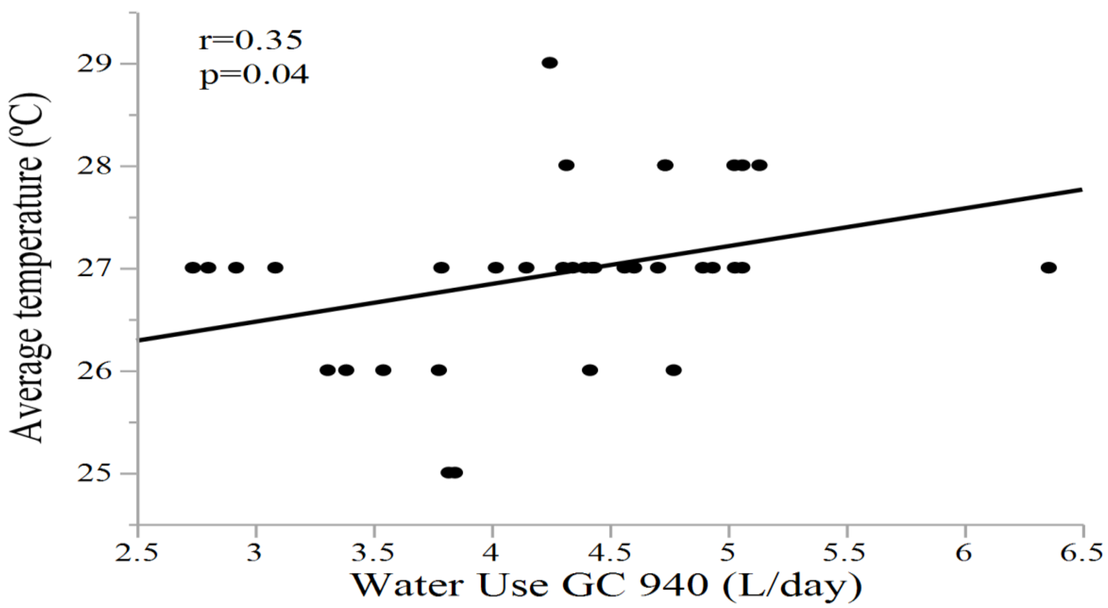

Figure 8: Influence of temperature on water use by Eucalypt clones at Kongowe-Kibaha, Tanzania

Sap velocity patterns

The results further revealed that, different clones showed different patterns of sap velocity in wet and dry seasons (Figure 9). During wet season, sap velocity increased rapidly in the morning at 08.30 am and thereafter decreased sharply at the middle of the day due to high rainfall followed by sharp increase (Figure 9a). A large rainfall event results in the sap velocity rate remaining depressed whilst a short rainfall event, the tree even increases its sap velocity as supported by (Carloy and Dragoni, 2009). During dry season after sharp increase at 08.30 am, sap flow remains almost constant for much of the remainder of the daylight hours probably due to small changes in weather condition (Figure 9b).

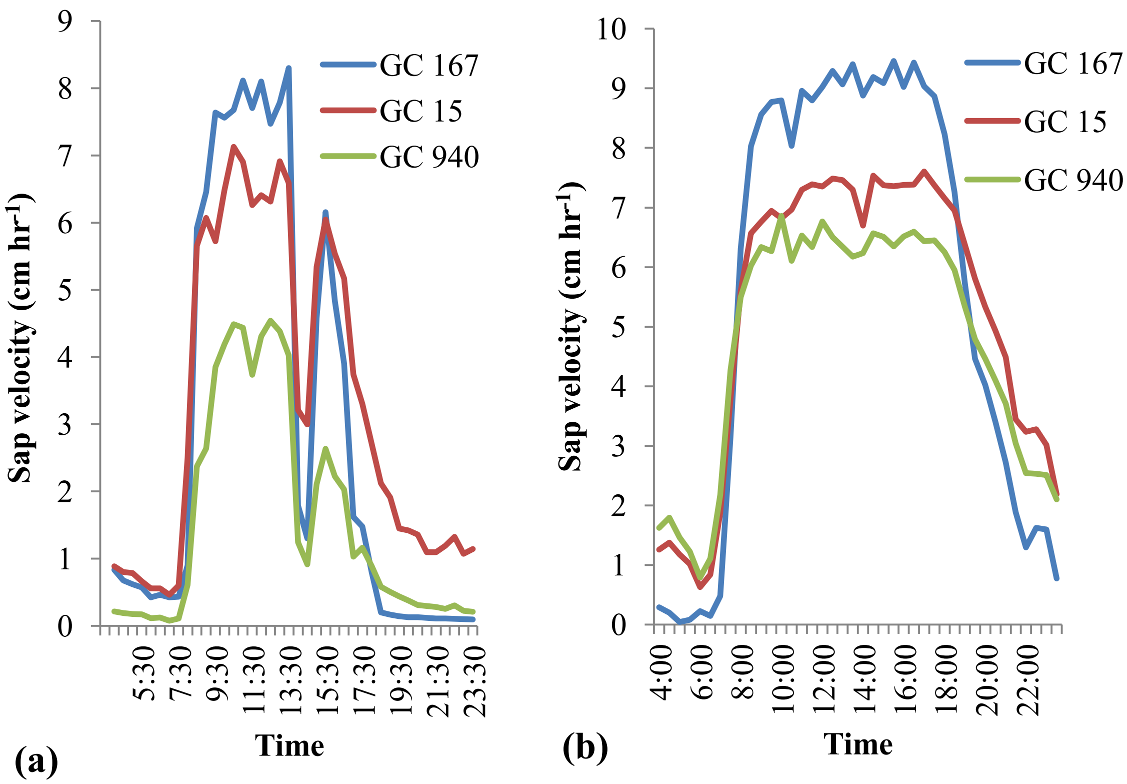

Figure 9: Hourly patterns of sap velocity of Eucalypt clones at Kongowe – Kibaha in (a) wet season and (b) dry season

As environmental conditions change, the proportionality of the velocities radially within the tree also changes, thus resulting in declining water use (Granier, 1987). As extended periods throughout the dry season do not experience any rainfall, tree water use remains equally unchanged during daytime as supported by Keitel and Adams (2009). These patterns can be interrupted by intense cloud cover, with acceleration of the effect if rain events accompany cloud cover (Keitel and Adams, 2009). Gush (2011) concluded that seasonal variations in sap velocity are highly correlated to climatic stimuli such as changes in temperature and day length.

4.3 Wood Properties

4.3.1 Physical properties

4.3.1.1 Basic density

4.3.1.1.1 Wood density variation between clones

Table 29 presents the results for mean basic density variation between clones at Lushoto, Kibaha, Kwamarukanga and Tabora sites. The results revealed that, the overall mean basic density for wood of all clones studied ranged from 525.50 kg m^{-3} to 633.99 kg m^{-3}. The results indicated significant ($p<0.05$) difference in mean wood basic densities for Eucalypt clones at Lushoto and Kibaha sites. However, there were no significant differences in mean basic densities between clones studied at Kwamarukanga and Tabora sites. GC 584 and GC 581 had significantly higher mean basic density values than GU 608 at Lushoto site. Wood of GC 940 and GC 15 at Kibaha site had significantly higher mean basic density values than GC 167. For Kwamarukanga site, wood of clones GC 940, GC 514 and GT 529 showed no significant difference in mean basic density values while wood of clones at Tabora site showed no significant difference between clones.

Table 29: Basic density of 9 year old Eucalypt clones in four sites

Site	Treatment	Basic density (Kg m^{-3})
Lushoto	GC 581	572.92a ±12.19
	GC 584	587.85a ±19.42
	GU 608	525.50b ±13.06
Kibaha	GC 15	585.89a ±20.17
	GC 940	598.54a ±16.09
	GC 167	532.91b ±18.48
Kwamarukanga	GC 514	633.99a ±18.13
	GC 940	593.07a ±17.61
	GT 529	616.70a ±10.54
Tabora	GC 584	537.08a ±9.00
	GC 940	532.06a ±7.05
	GC 15	540.60a ±6.02

Values with ± are standard error. Mean values followed by the same letter within a column and within a site do not differ significantly (p> 0.05) based on DMRT.

Table 30: Basic density of other *Eucalyptus* species

Species	Age (years)	Basic density (kgm−3)	Reference
E. grandis	9	497	Bhat *et al.* (1990)
E. grandis	8	426–532	Marcos *et al.* (1998)
E. grandis	7	490	Carvalho and Nahuz (2001)
E. grandis	10	517	Githiomi and Kariuki (2010)
E. globules	7	442–450	Miranda *et al.* (2001)
E. saligna	*	480	Muga *et al.* (2009)
E. grandis	*	450	Muga *et al.* (2009)

*Age not given

Mean basic density of 9 year old Eucalypt clones at the four study sites varied between clones within a site. The differences in mean basic density between clones may be a result of differences in the anatomy of wood such as vessel characteristics, type of cells, their proportions and arrangements as well as the accumulation of extractives in heartwood in individual hybrids (Panshin and De Zeeuw, 1970; Gominho *et al.,* 2001 and Turinawe *et al.,* 2014). The differences may also be due to intrinsic differences in growth rates of the individual trees sampled (Muga *et al.,* 2009). The mean basic density values obtained in this study were relatively similar to the results reported by other researchers (Purkayastha *et al.,* 1979; Carvalho and Nahuz, 2001; Santos *et al.*, 2011; Pereira *et al.,* 2012) for 7 to 9 year old Eucalypt clones. The results are also similar to those reported for

Eucalypt clones in Kenya and Uganda (Muga *et al.,* 2009 and Turinawe *et al.,* 2014). However, study results are slightly higher than those reported by Rezende *et al.* (2010) and Zanuncio *et al.* (2013) for 7 year old for *E. urophylla* clone. The mean basic density for Eucalypt clones are higher than those reported in Table 30. According to Ikemori *et al.* (1986) and Miranda *et al.* (2001), wood basic density in the range of 480 kg m^{-3} to 650 kg m^{-3} is ideal for pulp and paper production. On the other hand, Kityo and Plumptre (1997) reported that timber for structural use should have density of 400 - 750kg m^{-3}. When considering only wood basic density, the clones have potential to produce charcoal, because all clones had values higher than the average suggested by Trugilho *et al.* (2001) and Santos *et al.* (2011). The authors reported that basic density for the production of charcoal should not be less than 500 kgm^{-3}. The wood of the clones studied is therefore suitable for pulp and paper raw materials, charcoal and timber production where the required basic density is met.

4.3.1.1.2 Wood density variation within clones

Axial variation

Axial variation in basic density of Eucalypt clones is presented in Figure 10. The results revealed that wood density varied from 550 to 598 kg m^{-3} for GC 581, 510 to 574 kg m^{-3} for GU 608 and 566 to 585 kg m^{-3} for GC 584 at Lushoto site. The basic density of GC 581 and GU 608 clones increased from the bottom to the top of the tree while GC 584 decreased from bottom to the middle and then increased towards the top (Figure 10a). However, their differences were not statistically significant (P = 0.2881, P = 0.1288 and P = 0.4368) for GC 581, GU 608 and GC 584 respectively. At Kibaha site, basic density varied in axial direction from 525 to 546 kg m^{-3} for GC 167, 566 to 605 kg m^{-3} for GC 15 and 568 to 640 kg m^{-3} for GC 940. Wood density values increased from the bottom to the middle and then slightly decreased towards the top (Figure 10b). However, these variations were not statistically difference (P = 0.8268, P = 0.7103 and P = 0.1712) for GC 167, GC 15 and GC 940 respectively. At Kwamarukanga site, wood basic density for clones varied in axial direction from 607 to 633 kg m^{-3} for GT 529, 527 to 655 kg m^{-3} for GC 940 and 630 to 652 kg m^{-3} for GC 514. Wood basic density increased from the bottom to top for GC 940 and the differences are statistically significant (P = 0.0227). For GC 514 and GT 529, the basic density decreased from bottom to the middle and then increased towards the top though their differences were not statistically different (P = 0.9061 and P = 0.7553) for GC 514 and GT 529 respectively (Figure 10c). At Tabora site, wood basic density varied in axial direction from 521 to 547 kg m^{-3} for GC 940, 524 to 548 kg m^{-3} for GC 15 and 531 to 545 kg m^{-3} for GC 584. Basic density of clones increased from the bottom to the middle and then decreased towards the top for GC 15 and GC 584 while GC 940 showed that the basic density decreased from bottom to the middle and then increased towards the top. These variations were not statistically different (P = 0.4036, P = 0.8287 and P = 0.4378) for GC 15, GC 584 and GC 940 respectively (Figure 10d).

The wood basic density values of some Eucalypt clones increased in axial direction from bottom to the top of the tree while other clones showed an initial decline of wood density before increasing upwards. This behaviour is in contradiction with systematic variation of wood properties along tree height which asserts that as a rule, the heaviest wood is found at the base of a tree (Desch and Dinwoodie 1996). This kind of variation can probably be explained by differences in cellular structure, i.e. fibre length and diameter at different levels along the tree height of Eucalypt clones (Turinawe *et al.,* 2014).

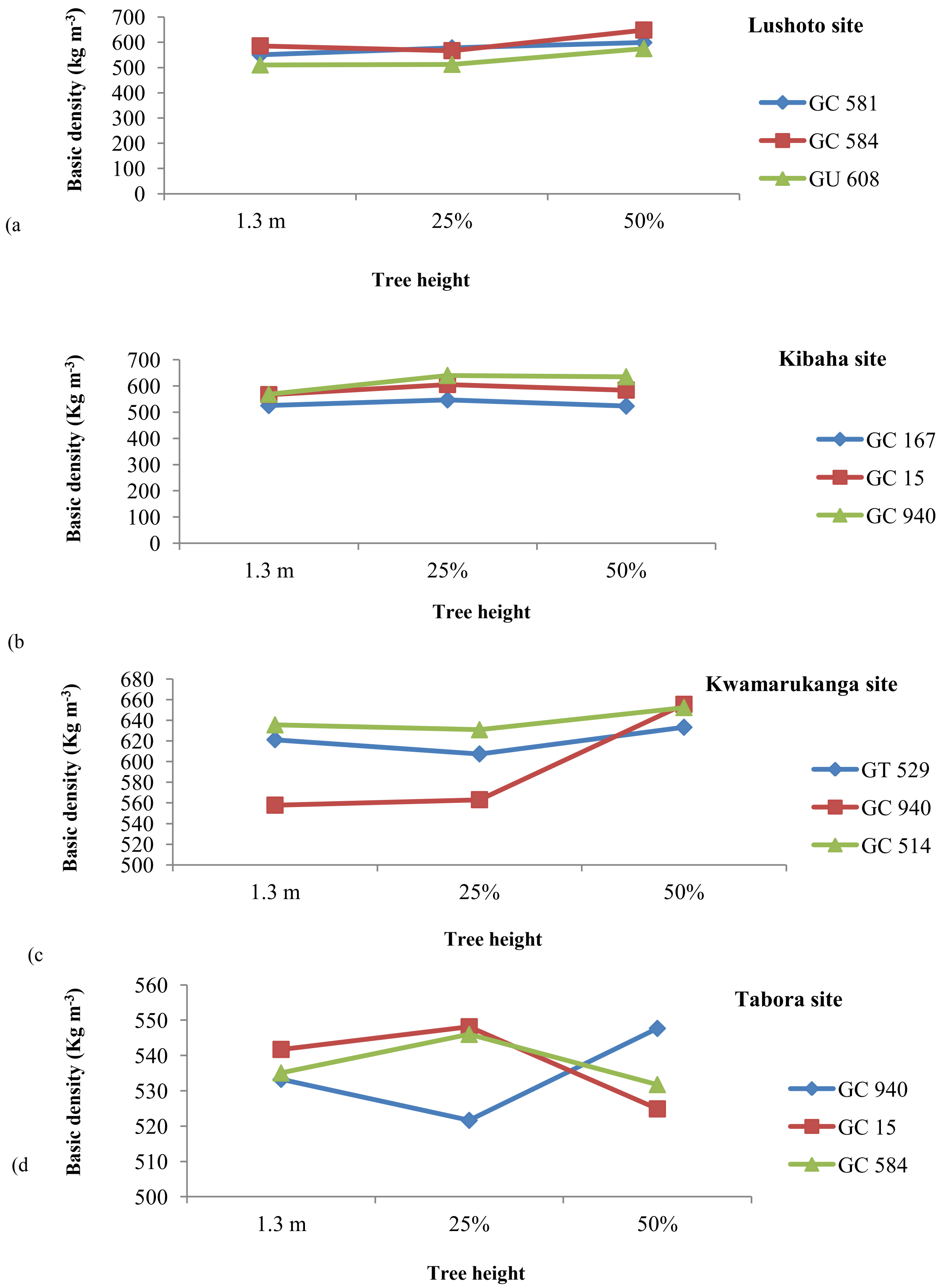

Figure 10: Axial variation in basic density of Eucalypt clones at Lushoto, Kibaha, Kwamarukanga and Tabora sites

According to Wilkes (1988) and Zobel and Van Buijtenen (1989) wood density of Eucalypts increases with tree height from bottom to the top. However, the initial decline of wood density between 5% and 15% height levels before the increase upwards was also reported for some species, namely *E. globulus* and *E. nitens* (Raymond and Mineri, 2001), *E. globulus* (Quilhó and Pereira, 2001) and *E. glandis x E. urophylla* hybrid (Quilhó *et al.,* 2006).

The axial increase of wood density could reflect the increase of fibre wall thickness from the base to the top and a possible variation of vessel dimensions and percentage which has been observed by Quilhó and Pereira (2001). The axial variation patterns obtained in this study may also be explained in terms of the genetic differences and amount of extractives present, among other factors. Clone GC 940 at Kibaha site showed a different trend compared to the same clone at Kwamarukanga and Tabora sites which might be a result of site effect including soil characteristics, altitude and temperature of study sites.

4.3.1.2 Fibre length of Eucalypt clones

4.3.1.2.1 Variation between clones

Fibre lengths of Eucalypt clones from all the studied sites are presented in Table 31. The overall mean fibre length ranged from 0.857 mm to 0.969 mm for all clones at all sites. Fibre length differed significantly ($p<0.05$) between clones at Kwamarukanga, Kibaha and Tabora sites. However there were no significant differences in fibre lengths was recorded for all clones at Lushoto site. Wood of studied clones at Lushoto site showed that, fibre length for GU 608 was significantly higher than GC 584 but insignificantly higher than GC 581. At Kibaha site, wood of clone GC 940 and GC 15 showed significantly higher mean fibre length than GC 167. However, at Kwamarukanga site, clone GC 514 showed significantly higher mean fibre length than GC 940 and

GT 529 while GC 15 and GC 940 showed significantly higher mean fibre length than GC 584 at Tabora site.

Table 31: Fibre length of 9 year old Eucalypt clones in four sites

Site	Treatment	Fibre length (mm)
Lushoto	GC 581	0.925b ±0.007
	GC 584	0.934ab ±0.008
	GU 608	0.954a ±0.010
Kibaha	GC 15	0.921b ±0.008
	GC 940	0.969a ±0.010
	GC 167	0.942b ±0.008
Kwamarukanga	GC 514	0.959a ±0.010
	GC 940	0.898b ±0.007
	GT 529	0.916b ±0.010
Tabora	GC 584	0.857b ±0.007
	GC 940	0.942a ±0.007
	GC 15	0.922a ±0.008

Values with ± are standard error. Mean values followed by the same letter within a column and within a site do not differ significantly (p> 0.05) based on DMRT.

Variation in mean fibre length between Eucalypt clones within a site was observed in all study sites. These variations could be attributed to their genetic differences and anatomical structure namely cell types, size and proportions as reported by Panshin and De Zeeuw (1970) and Veenin *et al.* (2005). Eucalypt clones showed fibre length similar to those reported for *E. grandis* × *E. urophylla* clone trees (Grzeskowiak *et al.,* 2000; Carvalho and Nahuz, 2001), *E. grandis* parent trees (Bhat *et al.,* 1990), *E. camaldulensis* clones and other *E. camaldulensis* trees (Veenin *et al.,* 2005; Quilhó *et al.,* 2006) whose fibre length ranged between 0.8 mm to 1.3 mm.

However, the mean fibre length values in this study were higher than mean fibre length of 0.67 mm to 0.75 mm for Eucalypt hybrid clones (Dutt and Tyagi, 2011), 0.72 mm to 0.81 mm for Eucalypt clones and 0.70 mm for *E. camaldulensis* (El Moussaouiti *et al.,* 2012). According to Shackford (2003), generally hardwood pulps including *Eucalyptus* have normal fibre length of 1 mm while softwood pulps have a fibre length of 3.5 mm. Jorge *et* *al.* (2000) and Miranda *et al.* (2001) reported that Eucalypt clones with fibre length between 0.87 to 1.04 mm are suitable for pulp and paper production. Fibre length is one of the important effective features influencing pulp and paper quality, and long fibers enhance strength properties of paper (Naji *et al.,* 2013). The wood of the clones studied are therefore suitable for pulp and paper production.

4.3.1.2.2 Axial variation within clones

The axial fibre length variations of wood of Eucalypt clones from Lushoto, Kibaha, Kwamarukanga and Tabora sites are presented in Figure 11. The axial pattern of fibre length variation in Eucalypt clones at Lushoto site increased from bottom to middle and then decreased at higher level for GC 581 and GC 584 (Figure 11a) and for GU 608, decreased from bottom to middle then increased to the top. However, these variations were not statistically significant (P = 0.8380; P = 0.7888 and P = 0.5054) for GC 581, GC 584 and GU 608 respectively. Fibre length for clones at Kibaha site increased from the bottom towards the top for GC 15 and GC 940 while for GC 167, decreased from bottom to middle then increased to the top (Figure 11b). However, these variations were not statistically different (P = 0.9574, P = 0.1712 and 0.6818) for GC 15, GC 940 and GC 167 respectively. At Kwamarukanga site, fibre length variation of clones increased from the bottom to the middle and then decreased towards the top for GC 940 and GT 529 while GC 514 decreased from bottom to the top of the tree (Figure 11c). However, these differences were not statistically significant (P = 0.4860, P = 0. 8532 and P = 0. 5370) for GC 940, GT 529 and GC 514 respectively. Axial variation in fibre length for clones at Tabora site decreased from bottom to the middle and then increased towards the top for GC 940 and GC 584 while in GC 15, the fibre length variation increased from the bottom to the middle and then decreased towards the top (Figure 11d). These variations were not statistically different (P = 0.0670, P = 0.7035 and P = 0.0821) for GC 940, GC 584 and GC 15 respectively.

The axial variation increased from bottom to the top of the tree. Wilkes (1988) has described the axial pattern of fibre length variation in Eucalypts as an initial increase and then a decrease at higher levels. This pattern was found in various mature Eucalypts, *e.g.* in *E. globulus* (Jorge *et al.* 2000), *E. regnans* (Bisset and Dadswell, 1949), *E. grandis* (Bhat *et al.* 1990). Valente *et al.* (1992) observed fibre length to decrease with tree height in 8 to 12 year old *E. globules* sampled at four heights, but Rao *et al.* (2002) found no definite trend of axial variation in clones of *E. tereticornis*. Bhat *et al.* (1990) reported that the height of tree has little effect on fibre length. On average, there was small axial variation (Figure 10) with a slight increase towards the top, while in other clone an increase to the 25% of tree height was noted followed by a decrease at 50% of tree height.

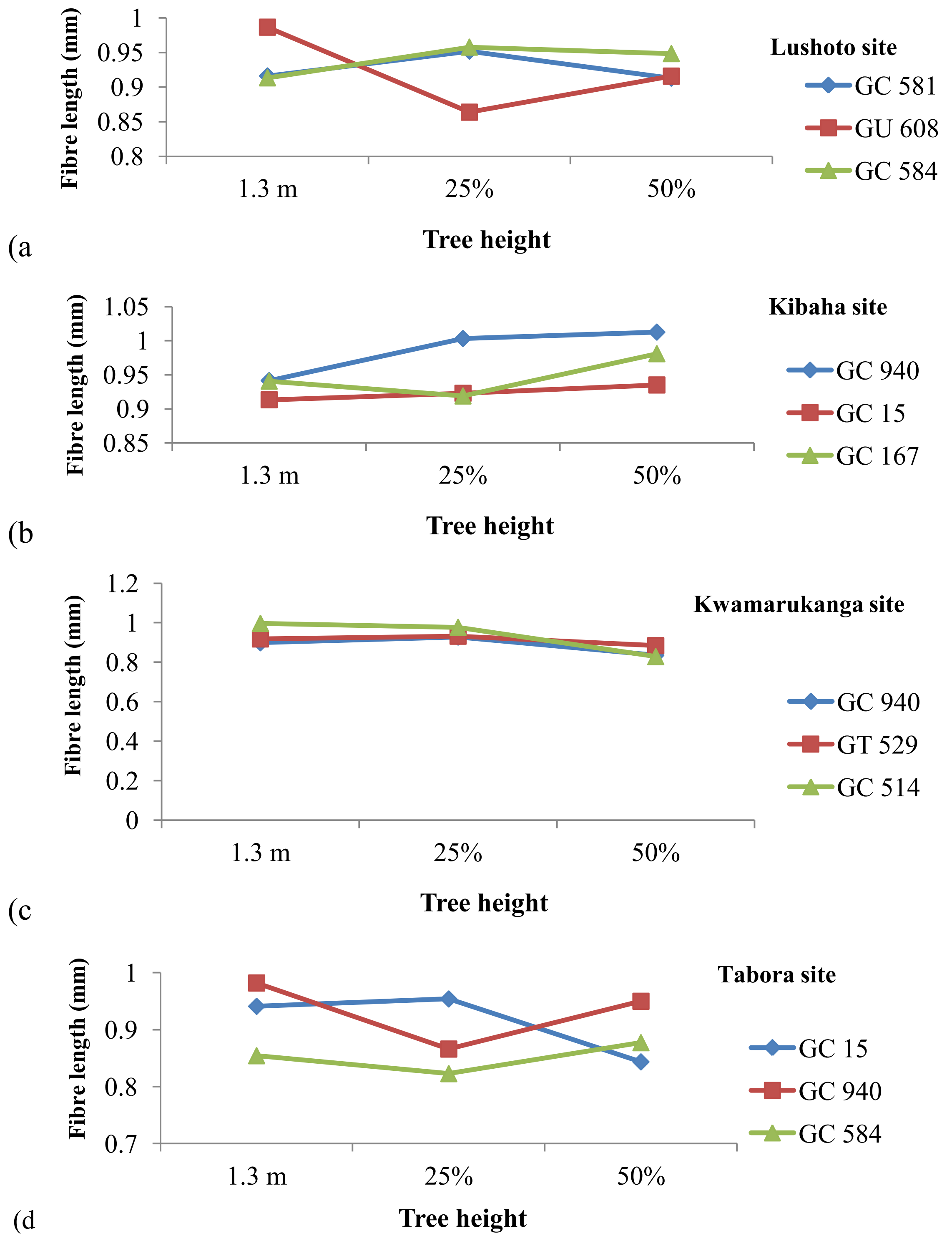

Figure 11: Axial variation in fibre length of Eucalypt clones at Lushoto, Kibaha, Kwamarukanga and Tabora sites

4.3.1.3 Relationship between Dbh and wood basic density

The relationships between Dbh and wood basic density of Eucalypt clones are presented in Figure 12. Regression analysis showed a positive linear relationship between Dbh and wood basic density for all Eucalypt clones in the study sites except for GC 584 at Lushoto site and GC 940 at Kibaha site. At Lushoto site, GC 581 and GU 608 recorded positive linear relationship between Dbh and wood basic density though not statistically significant (P=0.95713, P= 0.23777). GC 584 showed significant (P=0.01478) and negative relationship between Dbh and wood basic density (Figure 12a). For Kibaha site, GC 15 and 167 showed insignificant and positive linear relationship between Dbh and wood basic density (P=0.22399, P=0.07230) respectively. GC 940 showed insignificant and negative linear relationship (P=0.25649; Figure 12b). For Kwamarukanga site, insignificant and positive linear relationship between Dbh and wood basic density was observed (P=0.15808, P=0.70254, P=0.11122; Figure 12c) for GC 514, GC 940 and GT 529 respectively. GC 584 at Tabora site recorded significant and positive linear relationship between Dbh and wood basic density (P=0.01489). CG 940 and GC 15 showed insignificant and positive relationship between Dbh and wood basic density (P=0. 26425, P=0.11476; Figure 12d). Between sites, GC 940 showed insignificant and positive linear relationship between Dbh and wood basic density at Kwamarukanga and Tabora sites while at Kibaha site showed negative linear relationship.

(d

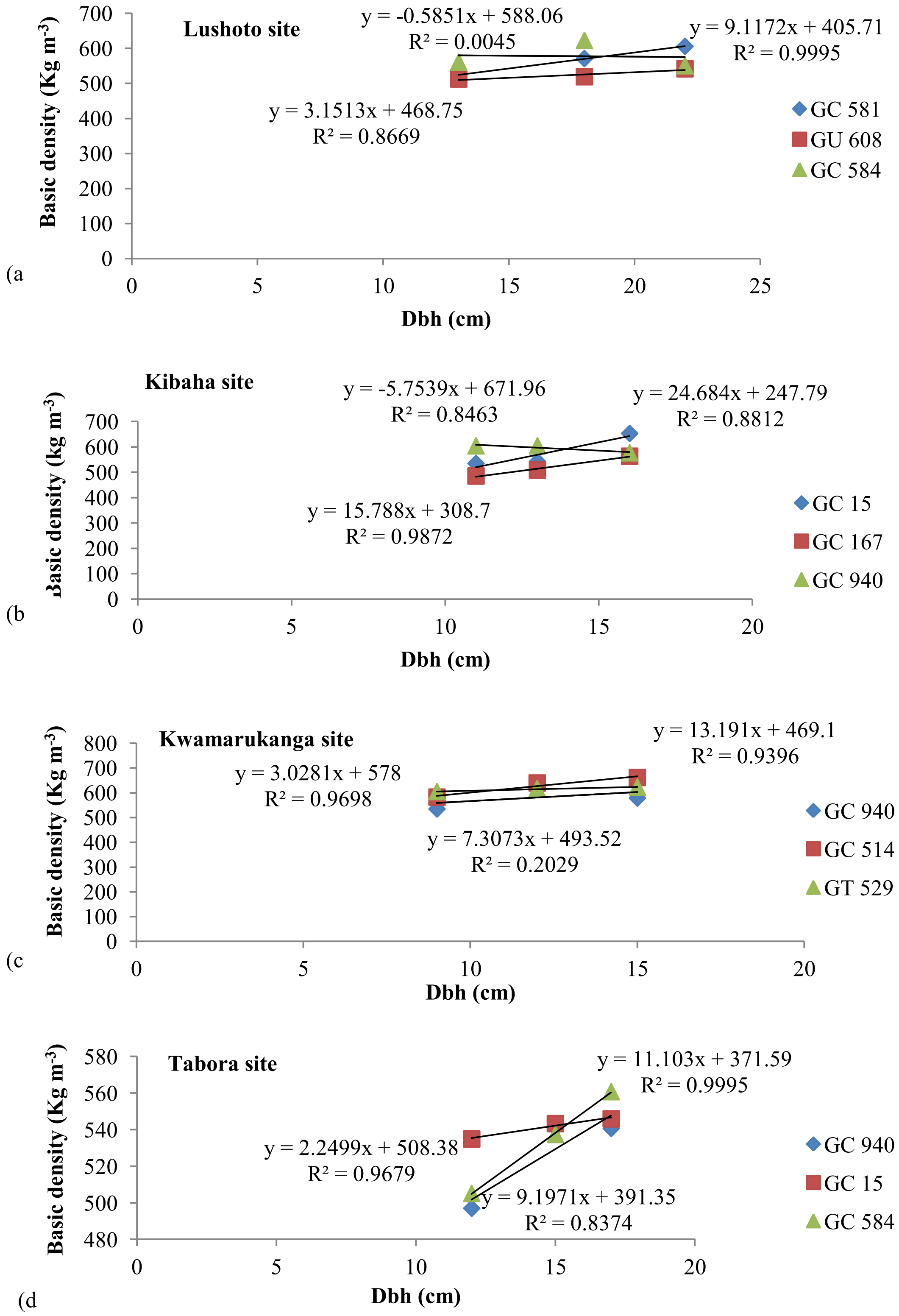

Figure 12: Relationship between Dbh and basic density of Eucalypt clones at Lushoto, Kibaha, Kwamarukanga and Tabora sites

The wood density was higher for clones at Kwamarukanga site with small diameter trees. This is in confirmation to the previous reports that growth rate is negatively correlated with wood density in *E. globulus* (Pereira and Araujo, 1990; Miranda *et al.*, 2001). Raymond and Muneri (2001) indicated that site quality has a considerable effect on wood density and better quality sites exhibited lower densities for *E. globulus* and *E. niten*. Muller-Landau (2004) reported that an increase in basic density was associated with a decrease in soil fertility. In drier regions where trees become retarded in growth, such tree produces wood of higher density (Batajas-Morales, 1987). Retardation and stunted growth of trees results in the formation of reaction wood (tension wood in hardwood) which influences density. Tension wood has higher density in comparison to normal wood (Tsoumis, 2009).

The study indicated positive relationship between Dbh and wood basic density of the studied Eucalypt clones for all sites with the exception of GC 584 at Lushoto site and GC 940 at Kibaha site. All Eucalypt clones except GC 584 at Lushoto site and GC 940 at Kwamarukanga site showed a strong coefficient of determination implying that Dbh is one of the factors influences wood basic density of the clones. GC 940 at Kibaha, Kwamarukanga and Tabora sites showed different trend of linear relationship between Dbh and basic density. This can be explained by environmental factors such as soil type, temperature, altitude and soil pH between sites (Table 1). Muga *et al.* (2009) reported that site has an effect on the basic and green density of GC hybrid clones. Quilho and Pereira (2001) showed that the wood basic density in *E. globulus* differed depending on the sites where they were grown.

4.3.2 Mechanical properties

4.3.2.1 Modulus of elasticity (MOE)

Table 32 presents results for mean MOE of studied wood of Eucalypt clones in all studied sites. The results revealed that the overall mean MOE for the studied clones at four sites ranged from 8525.16 Nmm^{-2} to 12710.42 Nmm^{-2}. The results indicated significant ($p<0.05$) difference in MOE values for wood of Eucalypt clones growing at Kibaha and Kwamarukanga sites. However, there were no significant differences in mean MOE for clones at Lushoto and Tabora sites. Wood of studied clones growing at Lushoto site showed that MOE for GU 608 was significantly higher than GC 584 but insignificantly higher than GC 581. For Kamarukanga site, wood of studied clones showed that MOE for GT 529 was significantly higher than GC 940 but insignificantly higher than GC 514. For Kibaha site, wood of studied clones showed significantly higher mean MOE value for GC 15 than for GC 167 and GC 940 while at Tabora site, studied clones showed no significant difference between clones.

Table 32: Modulus of elasticity of 9 year old Eucalypt clones from four sites

Site	Treatment	MOE (N mm^{-2})
Lushoto	GU 608	10252.83a ±351.51
	GC 581	9620.21ab ±404.42
	GC 584	8880.28b ±561.12
Kwamarukanga	GT 529	11498.53a ±421.15
	GC 514	10368.90ab ± 604.91
	GC 940	9110.39b ±564.70
Kibaha	GC 15	12701.42a ±1030.20
	GC 940	8525.16b ±1153.47
	GC 167	9096.30b ± 519.53
Tabora	GC 584	9048.87a ±279.69
	GC 940	8960.67a ±432.16
	GC 15	9090.39a ±316.87

Values with ± are standard error. Mean values followed by the same letter within a column and within a site do not differ significantly ($p> 0.05$) based on DMRT.

Modulus of Elasticity of wood of Eucalypt clones at the four study sites varied between clones within a site. This variation in MOE values was probably attributed to their genetic differences and anatomical characteristics that play a major role in variation between trees of the same age growing on similar site (Bhat and Priya, 2004; Turinawe *et al.,* 2014). Environmental conditions, soil type (Abbas *et al.,* 2010) and extractive content (Walker, 1993) may also cause this variation between trees. On the other hand, the difference in MOE values between clones could be associated with thicker fibre wall and longer fibre length. The thicker fibre wall and long fibre gave higher MOE as reported by Bhat and Priya (2004) and Nordahlia *et al.* (2014). The greater the MOE the stiffer the timber and conversely, the lower the MOE the more flexible it is.

MOE values ranging from 8525.16 Nmm^{-2} to 12710.42 Nmm^{-2} for wood of Eucalypt clones. The values are similar to those reported in similar studies on Eucalypt clones and other *Eucalyptus* species. For instance, Muga *et al.* (2009) reported MOE values which ranged from 7866 Nmm^{-2} to 15080 Nmm^{-2} for Eucalypt clones and 8335 N mm^{-2} to 11892 Nmm^{-2} for *E. grandis, E. tereticornis, E. camaldulensis* and *E. saligna* local landraces in Kenya. Olufemi and Malami (2011) reported MOE for *E. camaldulensis* ranging from 9048.49 to 19388.71 Nmm^{-2} in Nigeria and Moura (2000) in Hein and Lima (2012) reported MOE values of 9159 Nmm^{-2} for 9 year old *Eucalyptus* hybrid in Brazil. Acosta *et al.* (2008) and Hein and Lima (2012) found slightly lower MOE values which ranged from 6590 N mm^{-2} to 8993 N mm^{-2} for *E. grandis* and Eucalypt clones in Brazil. According to Kityo and Plumptre (1997), timber for structural use should have MOE ranging from 6860 to 14700 N mm^{-2}. On the other hand, ASTM (1989) reported that MOE of the standard plywood ranges from 6,890 to 13,100 N mm^{-2}. Wood of Eucalypt clones studied has MOE values within the specified ranges and thus can be used for plywood and making structural elements such as tie beams, rafters and purlins in house construction.

4.3.2.2 Modulus of rupture (MOR)

Results for MOR from all studied sites are shown in Table 33. The results revealed the overall mean MOR values ranged from 72.59 Nmm^{-2} to 108.48 Nmm^{-2} for all clones at all sites. Significant ($p<0.05$) difference in MOR between clones was observed at Kwamarukanga site. However, no significant differences in MOR were recorded for clones at Lushoto, Kibaha and Tabora sites. Wood of studied clones growing at Lushoto site showed the lowest and highest mean MOR values for GC 584 and GC 581 respectively. For Kwamarukanga site, MOR for GT 529 was significantly higher than GC 514 and GC 940. Studied clones at Kibaha site showed the lowest and highest mean MOR values for GC 167 and GC 940 respectively while GC 15 and GC 940 wood recorded the lowest and highest mean MOR values respectively at Tabora site.

Table 33: Modulus of rupture of wood of 9 year old Eucalypt clones from four sites

Site	Treatment	MOR ($N\ mm^{-2}$)
Lushoto	GC 581	100.70a ±3.35
	GC 584	89.48a ±4.83
	GU 608	92.17a ±3.53
Kwamarukanga	GT 529	108.48a ±4.85
	GC 514	92.48b ±4.58
	GC 940	72.59c ±5.44
Kibaha	GC 15	74.88a ±9.07
	GC 940	83.64a ±5.05
	GC 167	74.40a ±6.51
Tabora	GC 584	95.15a ±2.90
	GC 940	96.48a ±2.57
	GC 15	91.30a ±3.60

Values with ± are standard error. Mean values followed by the same letter within a column and within a site do not differ significantly ($p> 0.05$) based on DMRT.

Eucalypt clones from the four studied sites had MOR values ranging from 72.59 Nmm^{-2} to 108.48 Nmm^{-2}. The differences in MOR between Eucalypt clones within a site could be attributed to difference in their anatomic structure such as cell types and proportions and also genetical differences resulting into differences in wood structure as reported by Abbas *et al.* (2010) and Turinawe *et al.* (2014).

The results from this study are in keeping with findings reported by Olufemi and Malami (2011) for *E. camaldulensis* and Muga *et al.* (2009) for Eucalypt clones and for *E. grandis*, *E. tereticornis, E. camaldulensis* and *E. saligna* landraces. Wood from GT 529 and GC 581 had the highest MOR values, implying that they can withstand relatively higher bending stresses while in service. These findings are supported by Thelandersson and Hansson (1999) who reported that MOR values of 93.4 Nmm^{-2} can withstand relatively higher bending stresses while in service. According to Kityo and Plumptre (1997), timber for structural use should have MOR values ranging from 39 to 132 N mm^{-2} and should be durable, easy to plane and nail. The wood of Eucalypt clones studied had MOR values within the specified ranges and thus can be used for making structural elements such as tie beams, rafters and purlins in house construction.

4.3.2.3 Radial and Tangential Cleavage

The mean cleavage strength in radial and tangential direction for Eucalypt clones from all studied sites is presented in Table 34. The results revealed that the overall mean radial strength ranged from 13.51 Nmm^{-2} to 20.64 Nmm^{-2} and tangential strength ranged from 14.88 Nmm^{-2} to 22.02 Nmm^{-2} for studied clones at all sites. Wood of studied clones at Tabora site showed higher cleavage strength in radial and tangential direction for GC 584 and GC 15 respectively followed by Kwamarukanga, Kibaha and Lushoto sites. There were significant ($p<0.05$) differences in radial direction for wood of studied clones at

Tabora site. There were significant ($p<0.05$) differences in tangential strength for wood from Lushoto and Tabora sites. The results revealed no significant difference in radial and tangential strength for wood of studied clones at Kwamarukanga and Kibaha sites.

Table 34: Radial and Tangential Cleavage of wood of 9 year old Eucalypt clones from four sites

Sites	Treatment	Cleavage strength at Test (N mm^{-2})	
		Radial	**Tamgential**
Lushoto	GC 581	15.98a ±0.92	14.88b ±1.09
	GC 584	15.84a ±1.85	19.12a ±1.77
	GU 608	13.51a ±0.65	15.64b ±0.73
Kwamarukanga	GC 514	19.94a ± 1.43	19.89a ±1.53
	GC 940	16.56a ±1.07	16.74a ±1.30
	GT 529	19.19a ±1.03	20.41a ±1.72
Kibaha	GC 15	16.99a ±1.46	20.17a ±1.00
	GC 940	17.24a ±0.71	18.89a ±1.17
	GC 167	16.52a ±1.15	17.24a ±0.85
Tabora	GC 584	20.64a ±1.85	21.41a ±1.77
	GC 940	15.57b ±0.65	16.47b ±0.73
	GC 15	18.18ab±0.92	22.02a ±1.09

Values with ± are standard error. Mean values followed by the same letter within a column and within a site do not differ significantly ($p> 0.05$) based on DMRT.

Cleavage resistance is an important property in practical use of wood as fuel, as it determines the ease of splitting. Wood with low cleavage resistance splits readily under a wedge force in the radial direction (Zziwa *et al.* 2006). Variation in cleavage strength values between Eucalypt clones within a site was observed in all study sites. This could be explained by differences in arrangement and orientation of fibers leading to straight or spiral grain Turinawe *et al.* (2014). FPL (2010) reported that straight grained timber split more readily radially than tangentially, and more readily dry than green, but timbers with markedly interlocked grain split more readily tangentially and are often extremely difficult to split radially. The same author also pointed out that the readiness of a timber to split, which cleavage denotes has a practical application in certain circumstances. For instance in firewood and material for the manufacture of tight barrels, charcoal and hand-split shingles, high cleavage is a very desirable asset.

The cleavage strength values obtained in this study are similar to those reported by Turinawe *et al.* (2014), who documented cleavage strength ranging from 18 to 20 Nmm^{-2} for Eucalypt clones and 16 to 33 Nmm^{-2} for *E. camaldulensis* in Uganda. The results also revealed the tangential cleavage strength from Eucalypt clones wood is higher than in radial direction. Similar results were reported by Moya and Muñoz (2010) in their research, where cleavage at tangential direction was higher than radial direction. Similarly, Ismaili *et al.* (2013) reported that, cleavage strength at tangential direction possessed higher strength than radial direction for both green and an air-dry condition. Wallis (1970) found that, lower values of cleavage in radial direction were due to the relationship between air-dry density and the cleavage strength of timber along the fibres.

4.3.2.4 Compression strength (CS)

The results for compression strength parallel to grain are presented in Table 35. The results revealed that, the overall CS values of studied Eucalypt clones from all sites ranged from 41.94 Nmm^{-2} to 57.22 Nmm^{-2}. Significant ($p<0.05$) difference in compression strength was observed in samples from Tabora site. Samples from Lushoto, Kwamarukanga and Kibaha sites showed no statistical significant differences within each site. Wood of studied clones at Lushoto site showed the lowest and highest mean CS values for GU 608 and GC 581 respectively. Wood of studied clones growing at Kwamarukanga site showed the lowest and highest mean CS values for GT 529 and GC 514 respectively. For Kibaha site, wood of studied clones showed the lowest and highest mean CS values for GC 167 and GC 15 respectively. However, wood of studied clones at Tabora site showed the lowest mean CS values for GC 15 and highest mean CS values for GC 584 and GC 940.

Table 35: Compression strength of 9 year old wood of Eucalypt clones from four sites

Site	Treatment	Compression Force (N mm^{-2})
Lushoto	GC 581	57.22a ±1.52
	GC 584	57.17a ±3.28
	GU 608	56.56a ±2.45
Kwamarukanga	GC 514	50.42a ±2.06
	GC 940	50.32a ±1.60
	GT 529	49.70a ±2.11
Kibaha	GC 15	53.19a ±2.10
	GC 940	50.66ab ±2.16
	GC 167	46.89b ±1.44
Tabora	GC 584	48.81a ±1.55
	GC 940	46.20a ±1.55
	GC 15	41.94b ±0.77

Values with ± are standard error. Mean values followed by the same letter within a column and within a site do not differ significantly (p> 0.05) based on DMRT.

Compression strength is the resistance of wood to the forces which tends to shorten the wood cells. The study results revealed significant variation in compression strength values between clones. The differences in mean compressive strength values between clones might be attributed to the presence of wood extractives and this is in agreement with Walker (1993). The author pointed out that extractives influence strength properties and this is a function of the amount of extractives, the moisture content of the piece and the compression strength under consideration.

Eucalypt clones studied showed compression strength similar to those reported by Moura (2000) in Hein and Lima (2012); Acosta *et al.* (2008); Awan *et al.* (2012) and Lima *et al.* (2014). The results from this study are higher than those reported by Lima *et al.* (1999) with compression strength values of 42 Nmm^{-2} for 8 year old Eucalypt clones. Malami and Olufemi (2013) reported compression strength values ranged from 53.81 to 68.52 Nmm^{-2} for *E. camaldulensis* in Nigeria higher than the results reported in this study. According to Muga *et al.* (2009), Eucalypt clones had significantly higher compression strength values than *E. grandis* and *E. tereticornis* progenies in Kenya.

4.3.2.5 Shear strength

Table 36 presents results for shear strength values of Eucalypt clones from the four studied sites. Results indicated that, the overall shear strength values of clones from all studied sites ranged from 7.75 Nmm^{-2} to 13.68 Nmm^{-2}. However, significant ($p<0.05$) differences in shear strength between Eucalypt clones was recorded at all sites. Wood of studied clones growing at Lushoto site showed significantly higher mean shear strength values for GC 581 and GC 584 than GU 608. For Kwamarukanga site, wood of studied clones showed significantly higher mean shear strength values for GT 529 than GC 514 and GC 940. Wood of studied clones at Kibaha site showed significantly higher mean shear strength values for GC 940 than GC 15 and GC 167 while for Tabora site, wood of studied clones showed significantly higher mean shear strength values for GC 15 and GC 584 than GC 940.

Table 36: Shear strength of 9 year old wood of Eucalypt clones from four sites

Site	Treatment	Shear strength (N mm^{-2})
Lushoto	GC 581	13.23a ±0.34
	GC 584	13.11a ±0.71
	GU 608	11.55b ±0.46
Kwamarukanga	GC 514	9.27b ±0.48
	GC 940	7.85c ±0.42
	GT 529	11.55a ±0.43
Kibaha	GC 15	11.24b ±0.72
	GC 940	13.68a ±0.62
	GC 167	9.96b ±0.54
Tabora	GC 584	11.31a ±0.29
	GC 940	10.25b ±0.27
	GC 15	11.59a ±0.29

Values with ± are standard error. Mean values followed by the same letter within a column and within a site do not differ significantly ($p> 0.05$) based on DMRT.

Shear strength is the ability to resist internal slipping of one part upon another along the grain. It is the measure of the resistance of the timber to break apart when subjected to sliding forces (Ishengoma and Nagoda, 1991). Shear strength values of Eucalypt clones varied between clones. The differences observed in shear strength between clones could be attributed to genetic differences (Ishengoma and Nagoda, 1991) and other localized site factors (Ringo and Klem, 1980). Madsen (1992) found that, the shear strength does appear to be affected somewhat by moisture content between green and air-dry condition.

Shear strength values recorded in this study are in the range of those reported by Acosta *et al.* (2007); Santos *et al.* (2011) and Lima and Garcia (2011) with shear strength values ranging from 10.7 to 13.8 Nmm^{-2} for *E. grandis* and *E. resinifera*. Wood from GC 584 and GC 581 at Lushoto site and GC 940 at Kibaha site have good shear values implying that they could be used as substitutes for structural purposes where toughness is desired. The results from shear tests are important for predicting the behaviour of wood when subjected to joining; hence, the lower shear strength presents design of joints problems (Walker, 1993). Albino *et al.* (2010) reported shear strength values for *E. grandis* W. Hill ex Maiden lower than the study results, yet several factors may have contributed to this difference, including species, standard or procedure used, tree age, site conditions and test type.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main objectives of this study was to determine the growth performance, water use and wood properties of Eucalypt clones growing in Lushoto, Kibaha, Kwamarukanga and Tabora sites. The results obtained led to the following conclusions.

i. Eucalypt clones studied showed significant differences in terms of survival, Dbh, height, basal area, volume and biomass production within a site with the greatest growth performance being shown at Lushoto site. Volume and biomass production in all clones in Lushoto site are equal to or better than those obtained elsewhere in the world.

ii. Further, the results indicated that clone GC 167 uses higher amount of water both in the dry and wet seasons than GC 15 and GC 940.

iii. The study also showed that there were significant variations in wood basic density between clones at Lushoto and Kibaha sites while at Kwamarukanga and Tabora sites showed no significant variation.

iv. Significant variation in fibre length was observed for Eucalypt clones at Kibaha, Kwamarukanga and Tabora sites while Lushoto site showed no significant difference.

v. In the axial direction, wood basic density and fibre length showed different patterns of variation in different Eucalypt clones. However, these variations were not statistically significant.

vi. Mechanical properties values for the studied Eucalypt clones meet the minimum requirements needed for different structural applications.

5.2 Recommendations

Based on the conclusions made from the study, the following recommendations are given concerning Eucalypt clones in Tanzania.

i. Based on high survival, Dbh, height, basal area, volume and biomass production, GC 581, GC 584 and GU 608 are recommended for Lushoto site. GC 15, GC 167 and GC 940 recommended for Kibaha site. GC 514, GT 529 and GC 940 recommended for Kwamarukanga site and GC 15, GC 584 and GC 940 recommended for Tabora site. They are also recommended for planting in areas with climatic and soil conditions similar to the sites where they were tested.

ii. Further research on performance of Eucalypt clones at rotation age, disease tolerance and effect of spacing before large scale planting of these clones in Tanzania needs to be carried out in order to explore wide information as a basis for Eucalypts planting.

iii. Eucalypt clones studied should be considered as a source of raw materials for pulp and paper, charcoal, timber for structural use and for structural elements such as tie beams, rafters and purlins in house construction.

iv. Further studies needs be carried out on water use efficiency of the studied Eucalypt clones. In this study, water use efficiency was not carried out due to time limitation. In order to assess water use efficiency, monitoring for water use and biomass production needs to be carried out for at least a year. This information will help to decide where these clones should be planted on the landscape to produce better outcomes.

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