BIOMASS PREDICTION MODELS FOR

COLOPHOSPERMUM MOPANE (MOPANE) IN BOTSWANA

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DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the owner of the copyright thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: 3 March 2009

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ABSTRACT

The aim of this study was to develop biomass prediction models for the determination of total aboveground biomass for mopane at three (3) study sites in Botswana. Thereafter, based on the pooled data from the three (3) study sites, recommend one cross-site biomass prediction model that could be used for the indirect estimation of the total aboveground biomass for mopane in Botswana.

All the data were collected by destructive sampling from three (3) study sites in Botswana. Stratified random sampling was based on the stem diameter at breast height (1.3 m from the ground). A total of 30 sample trees at each study site were measured, felled and weighed. The 30 sample trees were distributed equally between six *DBH* classes (Five sample trees per *DBH* class). Thereafter, using the data from these sample trees, site-specific biomass prediction models for the indirect estimation of total aboveground biomass for mopane were developed as a function of the following independent variables: stem diameter at 0.15 m from the ground; stem diameter at 1.3 m from the ground; stem diameter at 3 m from the ground; crown diameter; and total tree height. The data from the sites were pooled together to develop cross-site biomass prediction models as a function of the given independent variables.

The biomass prediction model that provided the best fit at Serule was a linear equation estimated by means of the stem diameter at 1.3 m, while in Sexaxa the biomass prediction model that provided the best fit was estimated by means of the stem diameter at 0.15 m. The biomass prediction model that provided the best fit at the Tamacha site was estimated by means of the stem diameter at 1.3 m. On the basis of the collected data, cross-site biomass prediction models were developed. The cross-site biomass prediction model that provided the best fit was developed from the stem diameter at 1.3 m. This relationship was adopted as the prediction model for the indirect biomass estimation of *Colophospermum mopane* (mopane) in Botswana.

Keywords: Botswana; *Colophospermum mopane*; crown diameter; regression; stem diameter; total aboveground biomass; total height

OPSOMMING

Die doel van hierdie studie is die ontwikkeling van modelle om die totale bogrondse biomassa vir mopaniebome by drie (3) groeiplekke in Botswana te skat. Daarna, geskoei op die saamgevoegde data van die drie (3) studie areas, om een oorkoepelende model aan te beveel wat gebruik kan word vir die indirekte skatting van die totale bogrondse biomassa vir mopanie in Botswana.

Die data is alles versamel deur destruktiewe bemonstering by drie (3) studie areas in Botswana. Gestratifiseerde ewekansige bemonstering gegrond op die stamdeursnit by borshoogte (1.3 m van die grond) is gebruik. 'n Totaal van 30 monsterbome is by elke studieplek gemeet, gekap en geweeg. Die 30 monsterbome is gelyk verdeel tussen ses *DBH*-klasse (Vyf monsterbome per *DBH*-klas). Daarna, deur gebruik te maak van die data afkomstig van hierdie monsterbome, is biomassa-modelle vir spesifieke groeiplekke ontwikkel vir die indirekte skatting van totale bogrondse biomassa vir mopanie as funksie van die volgende onafhanklike veranderlikes: stamdeursnit 0.15 m van die grond; stamdeursnit 1.30 m van die grond; kroondeursnee; en totale boomhoogte. Die data van die groeiplekke is saamgevoeg om biomassa-modelle oor groeiplek as 'n funksie van die bogenoemde onafhanklike veranderlikes te ontwikkel.

Die model vir die skatting van biomassa wat op Serule die beste gepas het was 'n liniêre vergelyking geskat deur middel van die stamdeursnit op 1.3 m, terwyl op Sexaxa is die model vir die skatting van biomassa wat die beste gepas het geskat deur middel van die stamdeursnit op 0.15 m. Die model vir die skatting van biomassa wat die beste gepas het by die Tamacha groeiplek is geskat deur middel van die stamdeursnit op 1.3 m. Oor-groeiplek modelle vir die skatting van biomassa is ontwikkel op grond van die saamgevoegde data. Die oor-groeiplek model vir die skatting van biomassa wat die beste gepas het is ontwikkel van die stamdeursnit op 1.3 m. Hierdie verwantskap is aangeneem as die model vir die indirekte skatting van biomassa van *Colophospermum mopane* (mopane) in Botswana.

Sleutelwoorde: Botswana; *Colophospermum mopane*; kroondeursnit; regressie; stamdeursnit; totale bogrondse biomassa; totale hoogte

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1. INTRODUCTION

1.1   Aim and Objectives

The aim of this study is to support the conservation and management of mopane woodlands by examining the variation in woody biomass in three *Colophospermum mopane* (mopane) woodland types prevalent in Botswana and the southern African region. Whereas the aim of this study is to assess the variation in mopane woody biomass, the objectives of this study are:

1. To determine the relationship between total aboveground tree biomass and the following tree parameters: stem diameter at 0.15 m; stem diameter at 1.3 m; stem diameter at 3 m from the ground; crown diameter; and total tree height; and

2. To provide a set of biomass prediction models that will predict the total tree aboveground biomass (stem plus branches and foliage) for individual mopane trees at the study sites, and the rest of Botswana.

1.2   Thesis structure

The Introduction (Chapter 1) presents the aim and objectives, motivation and background information of the study. The literature review is presented in Chapter 2. The detailed descriptions of the study sites, materials and methods are provided in Chapter 3, while the results and discussions are presented in Chapter 4. Chapter 5 covers the conclusions drawn from the study. The general discussion draws the results in such a way as to improve the understanding of the woody biomass production and influential factors in savannah natural woodlands. The information is synthesized in a manner that makes it useful for better management of the natural woodlands that are comparable to those found in the study sites. The general discussion highlights issues for further research arising from the study. These suggestions are meant to improve and guide long-term research efforts of which this study has formed the initial stages. An example of the data sheet used for collection of data in the field is attached as an appendix I.

1.3   Background information

Colophospermum mopane (Kirk ex Benth) Kirk ex J. Léonard Syn *Copaifera mopane* is a widespread and important tree species over much of Botswana and sub-tropical Africa. The woodlands dominated by *C. mopane* (mopane) cover an area of about 550 000 km^2 in its natural range in southern Africa (Mapaure, 1994). The woodlands in Botswana provide a wide range of wood and non-wood products that contribute significantly to the livelihood of the rural communities adjacent to them. In Botswana, woody biomass accounts for 80% of household energy consumption in urban centres and is the sole source of energy in rural areas where 76% of the population lives (Anon., 2000). Furthermore, wood dominates the energy sector and contributes at least 33% to the primary energy supply, and at least 43% to each of nett and final energy supply (Anon., 2002). However, the utilization of these products is largely unplanned and has in many situations resulted in over-exploitation of the woodlands.

Botswana has a land area of 581 730 km^2 and is situated in the centre of the southern African plateau (inset of Map 1.1) at a mean altitude of 1 000 metres above sea level. The country straddles the Tropic of Capricorn and other than prominent hills along the eastern and south-eastern corridor has a featureless to gently undulating topography. The whole of Botswana falls within the savannahs of southern Africa as a dry and dystrophic type of savannah. Savannahs are known to be determined by rainfall and soil type (Walker, 1985), and are typically characterised by the presence of both woody plants and grasses exerting strong influence on the ecological processes of primary production, hydrology and nutrient cycling (Sekhwela, 2000).

The natural vegetation in Botswana covers an area of about 525 600 km^2 (90%) of Botswana's land area of 581 730 km^2 (Totolo, 1997). The area of mopane woodlands in Botswana is 85 000 km^2, which represents 14.6% of Botswana's total land area. The mopane woodlands directly or indirectly support the livelihood of the majority of the rural population in its natural range through the provision of construction material, edible caterpillars, fuelwood, fruits and medicine.
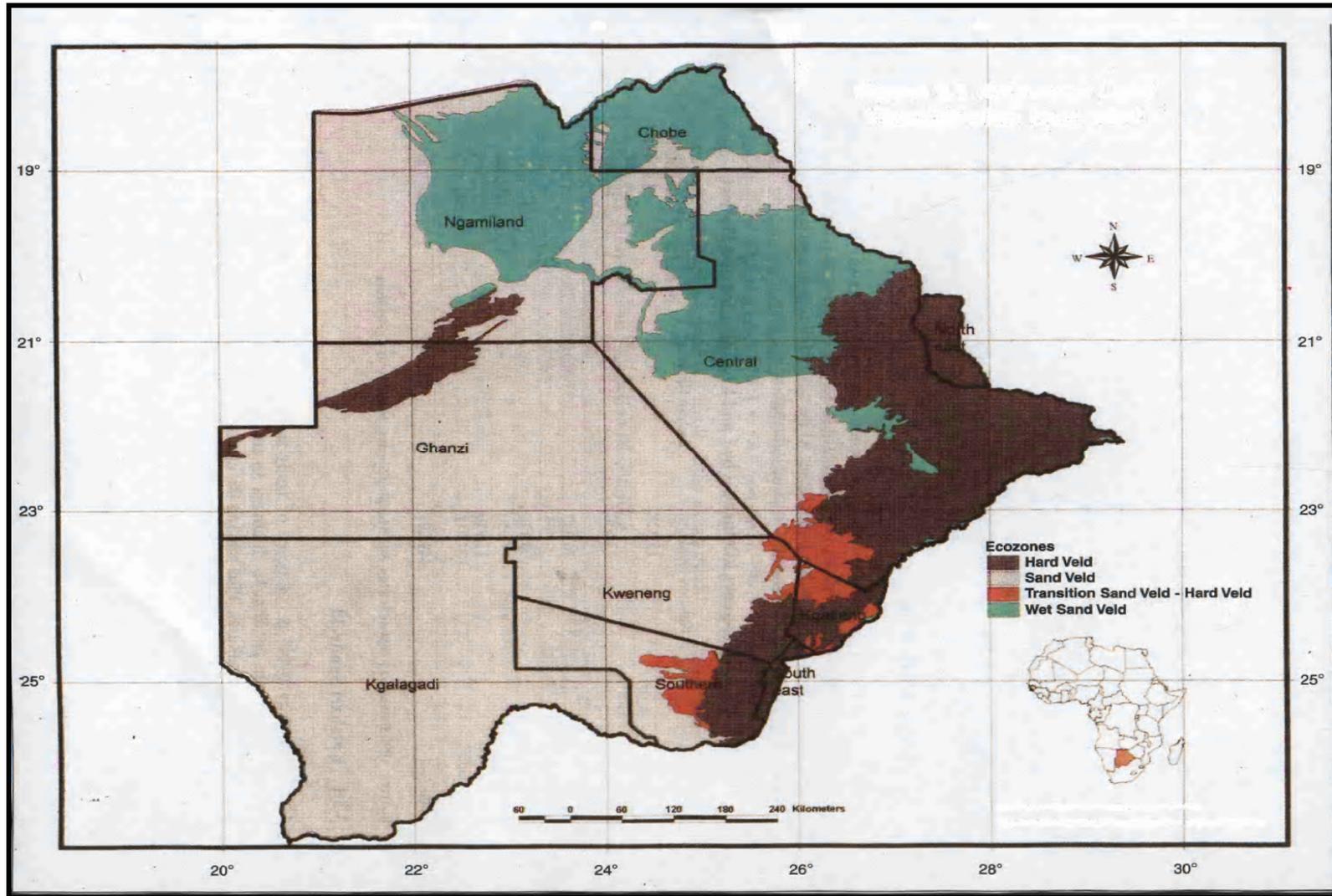
Map 1.1: Botswana land classification (Anon., 2000)

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About 77% (449 000 km^2) of Botswana's land surface is covered by the Kalahari sands, commonly referred to as the 'sandveld', while the remaining 23% (133 000 km^2) in the south-eastern, eastern and north-eastern parts of the country comprise the 'hardveld' land system with sandy loam and loamy sand soils that support the arable agriculture industry (Map 1.1) (Anon., 2000). The term 'veld' comes from 'veldt', originally the Afrikaans word for open grassland with or without bushes, shrubs and sparse forests, while the concept of 'veld types' was defined by Acocks (in Sekhwela, 2000) as a unit of vegetation with small variations allowing the whole of it to have the same farming potential. The use of this concept in the sandveld and hardveld context is to differentiate between the sandy substrate in the Kalahari and the 'hard' soils in other parts of the Botswana.

Climate has been identified as probably the single most important element of the natural environment of Botswana (Cooke, 1985); with arid to semi-arid conditions having a strong influence on the ecology and ecological processes of the dry savannah ecosystem (Sekhwela, 2000). Climate was found to account for 75% of the variation in plant species richness in southern Africa, with richness increasing with both precipitation and the length of the rainy season (Sekhwela, 2000).

In Botswana, rainfall is unpredictable over space and time, and varies considerably from year to year. The rainfall varies over the country from an average maximum of 600 mm in the northeast to an average minimum of 250 mm annual rainfall in the south-west (Map 1.2). Much of it falls in scattered showers with an uneven spatial distribution during the rainy (wet) season (October-April), and dry periods within the rainy season are common. The rest of the year is generally dry. High temperatures occur during the wet seasons with air temperature reaching over 40°C and soil temperature up to 70°C (Sekhwela, 2000). Consequently, evapo-transpiration is high, exacerbating moisture shortages.
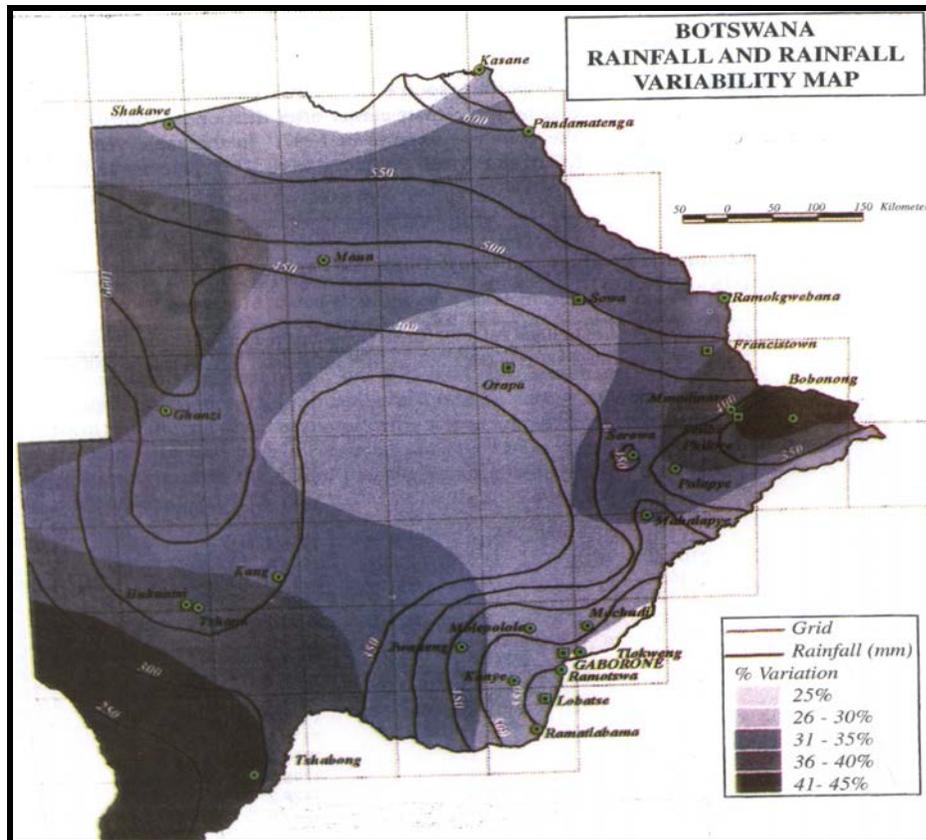
Map 1.2: Botswana rainfall and rainfall variability (Anon., 2000)

Kelly and Walker (1976) reported similar maximum temperatures of up to 71°C on bare exposed soil and noted the likely effect of this on plant growth in the savannahs of Zimbabwe. The available information shows that climate, soil type and nutrients could be the major factors influencing the distribution of the main vegetation types found in Botswana (Cooke, 1985; Parry, 1987). Rainfall in the Kalahari sands area declines from 600 mm per year in the extreme north to less than 250 mm in the south-west parts of the country and vegetation types change accordingly.

The Kalahari sands give a misleading impression of Botswana as a country covered by unproductive and expansive desert. In spite of the sand dunes that do occur in Botswana, especially in the west and south-west, the Kalahari is not a true desert. Rather, it is an area with low savannah vegetation. The relatively drier area in the far south west (250 mm annual rainfall) has mainly a shrub savannah type of vegetation dominated by *Acacia*[1] and other microphyllous species in the woody vegetation

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[1] At the time of writing, the *Acacia* in Africa was in the process of being renamed *Senegalia*

component. *Terminalia sericea* is common in much of the sandveld, forming dominant vegetation in association with *Lonchocarpus nelsii,* and sometimes various *Acacia* species including *A. erioloba*, *A. luederitzii*, and *A. mellifera*.

The relatively high rainfall (600 mm annual maximum) areas in the north, with loamy and sandy loam soils, have dry deciduous forests characterised by woody plant species that include *Baikiaea plurijuga, Brachystegia* spp*., Burkea africana*, and *Pterocarpus angolensis* (Anon., 2000).

The rest of the country has shrub to tree savannah dominated by *Colophospermum mopane* and *Acacia* species in the north-west and north-east, and *Acacia* and *Combretum* species in the south-east. The Okavango Delta in the north-west is characterised by complex vegetation communities and riverine woodland vegetation along its fringes (Ellery and McCarthy, 1974).

The herbaceous vegetation layer is composed predominantly of grass species, particularly in the grassland savannahs found in much of the Kalahari sandveld area (Skarpe, 1986). However, where livestock grazing has been intensive, resultant overgrazing has meant that grasses have been replaced by bushes (Skarpe, 1990) and annual herbaceous species that are relatively economically unimportant. This is particularly true of the hardveld system where livestock has been the mainstay of the rural economy for decades (Sekhwela, 2000). The livestock industry has expanded into the Kalahari sandveld system in the past few decades with the advent of borehole technology, and consequent vegetation changes have been observed (Skarpe, 1990; 1991).

1.4   Motivation for the study

Management of natural forests depends on information available concerning the growing stock; hence, the acquisition of forest growth information is a pre-requisite for any management system and sustainable land use (Chamshama, Mugasha and Zahabu, 2004). However, there is limited information on the pattern, trends and distribution of woody biomass production and of their primary, environmental and climatic determinants in different parts of Botswana. This has hindered the

development of techniques for the enhancement of woody biomass production for natural woodlands.

The limited information has also hindered the formulation of management strategies for comprehensive forest management and conservation policies by government. The information gap covers production and physiological ecology of woody vegetation, and extends to the whole of the arid and semi-arid savannahs of southern Africa. Efforts to improve the situation are quite limited despite the heavy reliance in Botswana of a large proportion of the population on woody biomass resources for energy and other household requirements.

Studies in southern Africa have produced predictive volume models for merchantable wood in timber and common canopy species (Banks and Burrows, 1966), and total woody biomass estimation models have been produced for regenerating woodlands (Grundy, 1995; Stromgaard, 1985; 1986; Tietema, 1993). However, few functions are available for the estimation of total tree biomass of woodland types such as *Colophospermum mopane* (mopane), where bole length is so variable and utilisation of branch wood is very common (Abbot, Lowore and Werren, 1997).

There have, however, been increasing efforts in recent years to improve the situation (Knoop and Walker, 1985; Sekhwela, 2000). For energy planning purposes, attempts have been made to estimate the amount of woody biomass available in Botswana forests and woodland savannahs using remote sensing techniques (Tietema, 1993). However, owing to a lack of understanding of the relation between on-the-ground biomass and spectral reflection measured by various satellites, the results of these studies were generally too inaccurate to be used for forest management purposes (Ringrose, Matheson and Dube, 1987).

This study, which focuses on biomass prediction models for mopane, contributes to the appropriate information concerning woody biomass production in Botswana and in the southern African region. As this study is based on direct field measurements, it avoids the problems experienced in previous studies in Botswana that were based on remote sensing techniques.

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2. LITERATURE REVIEW

2.1 Botany of mopane

Colophospermum mopane (Kirk ex Benth.) Kirk ex J. Léonard, commonly known as mopane, is the only species in the genus *Colophospermum*, which belongs to the Detarieae tribe of the sub-family Caesalpinioideae in the Fabaceae (Leguminosae) family (Mapaure, 1994; Timberlake, 1995). Other sub-families in the family are the Mimosoideae and the Papilinionoideae. Mopane can thus be botanically classified as follows:

Kingdom:	Plantae
Division:	Magnoliophyta
Class:	Magnoliopsida
Order:	Fabales
Family:	Leguminosae
Sub-family:	Caesalpinioideae
Genus:	*Colophospermum*
Species:	*C. mopane*

While Timberlake (1995) states that the generic name comes from the Greek word meaning "resinous seed", an illusion to the numerous scattered resin glands that cover the seeds, De Winter *et al*. (1996) cited in Timberlake (1995) on the other hand, states that the word comes from the Greek word meaning "seeds inhabiting the light". However, in reference to the glands that exude sticky fluid on the mopane seeds, Van der Schijff (1969) confirms that the word is a union of the Greek words *kolla* (gum), *phora* (produce), and *sperma* (seed). The species name is of native origin, and many African tribes use this name for the tree species.

The species is variously referred to as mopanie (Afrikaans), Rhodesian ironwood/mahogany, balsam tree, turpentine tree, mopane (English), omutati (Herero), ipane/ilipani (Ndebele), tsanya (Nyanja), omusati (Owambo), chanate (Portuguese), musharu/shanatse (Shona), nxanatsi (Sotho), mophane (Tswana), and mupani/mutanari (Venda) (Cunningham, 1996; Mapaure, 1994; Timberlake, 1995).

2.2   Morphology of mopane

2.2.1   Leaves

Mopane leaves consist of two large leaflets resembling butterfly wings, on a common petiole (Plate 2.1). The two leaflets are joined to each other and to the petiole by a very short, flat thickened portion. Leaflets are initially bright red-brown and very glossy. The leaves are approximately 8 cm long but sometimes as much as 20 cm in length and 3.5 cm wide, hard and brittle with an entire margin. Old leaves are pale green on both surfaces and retain the gloss on the upper side to a large extent. There are 7-9 conspicuous veins radiating from the base of each leaflet, a bulge on both surfaces, and no definite midrib is identifiable.

Leaflets

Plate 2.1: Mopane leaf
(http://www.plantzafrica.com/plantcd/colomopane.htm)
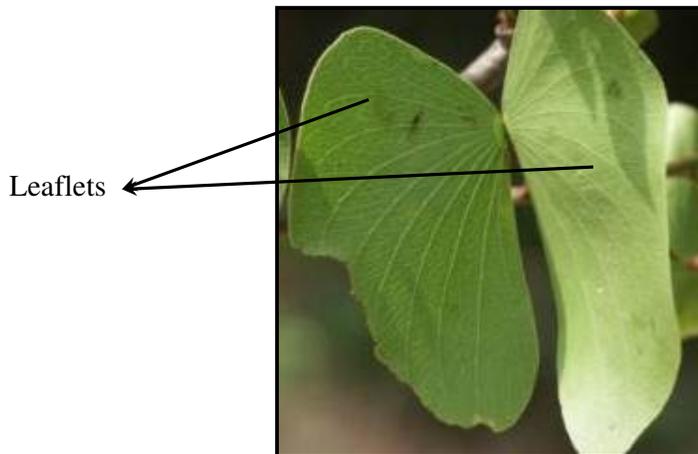
The leaves, which fall towards the end of the dry season, are alternate and most leaves have a petiole which is about 2.5 cm long. The stipules are large and fall off early (Palgrave, 2002; Palmer and Pitman, 1972; Van der Schijff, 1969).

2.2.2   Flowers

Flowers are unobtrusive, unattractive and inconspicuously small in short axillary raceme sprays. They are predominantly green in colour and borne in small drooping clusters in the leaf-axils near the terminals of the twigs. The flowers do not have petals but have about 4 sepals and 20-25 stamens that hang out of the flowers. Although the flowering season which varies between areas from October to March can be erratic, sometimes the trees in the whole region produce no flowers at all for

several years; the first sign of the blooming period is a mat of fallen flowers under the trees usually in December/January (Palgrave, 2002; Palmer and Pitman, 1972; Van der Schijff, 1969).

2.2.3   Fruits

The fruits are indehiscent, kidney shaped to oval, flat pods (Plate 2.2) that are borne in pendent clusters. Although the fruits turn brown when dry, they are green, leathery, and non-woody when fresh. The pods that are available from March to September are thin, semilunar in shape, about 5 cm long and 2 cm wide. A single large, flat, wrinkled, pale brown, roughly nephroid seed is contained in each pod. On both flat surfaces there are a number of small but conspicuous, reddish resinous glands, which exude a sticky fluid (Timberlake, 1995; Van der Schijff, 1969).
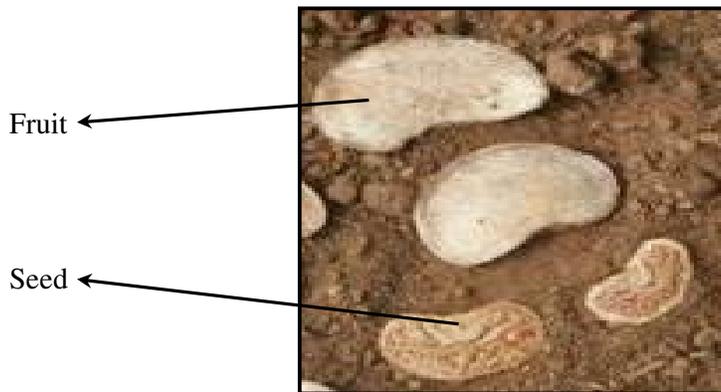
Plate 2.2: Mopane fruits and seeds
(http://www.plantzafrica.com/plantcd/colomopane.htm)

2.2.4   Stem

Mopane occurs in several physiognomic forms ranging from shrubs of between 1 and 2 m to tall-boled trees of up to 20 m in height (Palgrave, 2002; Palmer and Pitman, 1972; Smith, 1998), and may have stems of up to 150 cm in diameter (Timberlake, 1995; Van Wyk, 1972). New growth of the stem is smooth, pale brown and glabrous, while old stems are very rough, dark grey to almost white on the sunny side, but dark grey to almost black in the shade. The stem is characteristically deeply vertically fissured (Plate 2.3) and the bark flaking in narrow strips (Van Wyk, 1972).

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Plate 2.3: Mopane stem

2.3   Ecology of mopane

The species is endomycorrhizal (Grobbelaar and Clarke, 1972; Högberg and Piearce, 1986; Mlambo, Nyathi and Mapaure, 2005), which probably assists the tree in obtaining some of its nutrient requirements. However, as with all Caesalpinioideae, mopane does not have symbiotic nitrogen-fixing rhizobium within its roots i.e. it does not fix nitrogen (Grobbelaar and Clarke, 1972; Mlambo, Nyathi and Mapaure, 2005).   The seed has few parasites; germinates very easily through epigeal germination, and requires no pre-germination treatment (Msanga, 1998; Mushove, 1993; Tietema, Merkesdal and Schroten, 1992). Germination is rapid and even more rapid when the seeds are removed from the fruits (Tietema, Merkesdal and Schroten, 1992). However, mopane has a characteristically slow early growth and seedlings are usually recommended as planting stock to enhance fast growth (Palmer and Pitman, 1972). In the wet season, mopane coppices very well, with the tall stumps producing more coppice shoots than short stumps. Conversely, sprouting is achieved at a slower rate in thick and tall stumps than in thin and tall stumps (Mushove and Makoni, 1993).

The phenomenon of mopane occurring in both tree and shrub forms is well known. When made up of very tall trees reaching heights of 16-20 m, it is colloquially

termed "cathedral mopane" (Palgrave, 2002; Timberlake, 1995). This type is generally found on old and deep clay-rich alluvium. When soil conditions are not favourable and the plants remain stunted (2-6 m) such as on many *karoo* sediments and on sodium-rich, or on cracking clays, the mopane vegetation is referred to as "mopane scrub" (Palgrave, 2002; Timberlake, 1995).

According to Van Wyk (1972), the mopane tree-shrub phenomenon is found on shallow, badly drained soils, under which conditions mopane grows extremely slowly. In spite of the little experimental work that has been done on the mopane tree-shrub phenomenon, many authors suggest that the phenomenon may be ascribed to differences in effective rooting depth and soil moisture availability on different soils (Dye and Walker, 1980; Timberlake, 1995; Van der Schijff, 1969).

A study in Botswana showed that mopane occurred as trees in areas which have deep soils that are very rich in calcium, nitrogen, phosphorous, and potassium (Loso, 2003). The availability of these macro nutrients is essential for vigorous plant growth. The deficiency of nitrogen, and/or phosphorous would lead to slow growth and dwarfed plants, while the deficiency of calcium and/or potassium would lead to weak stalks and poor roots. In the same study, mopane height, cover and density also had a positive correlation with the cation exchange capacity (*CEC*) and the *pH* of the soil (Loso, 2003). Thus, as these soil properties increased, so did mopane height, cover and density. These physico-chemical properties of the soil are also important for the vigorous growth of plants. The *CEC* of the soil is the ability of soils to hold onto nutrients and prevent them from leaching beyond the roots. Therefore, the more *CEC* the soil has the more likely for it to have high fertility levels. The soil *pH* affects the availability of many plant nutrients because it has an effect on their solubility and release from organic matter by microbes. Many plant nutrients are available at or near neutral *pH*. Thus, if the soil is acidic, it becomes unfavourable for plant growth as many essential plant nutrients become unavailable.

Although mopane is a halophytic plant within its range in southern Africa (Henning and White, 1974), it will grow best in areas where there are no physical and chemical constraints (Lewis, 1991). Under these conditions, however, competing species are favoured and may exclude mopane. On the other hand, where soils have restricted

rooting depth, high sodium content, low infiltration rates, and high water holding capacity, mopane tends to dominate (Lewis, 1991; Mlambo, Nyathi and Mapaure, 2005). Mopane prefers heavy but medium textured soils with neutral-acidic *pH* levels, and it can tolerate moist and waterlogged soil conditions, and also survive dry saline sites. Most reported cases of the species occurring on sand probably refer to a thin sand layer, such as found on the Kalahari sands at the edges of pans or drainage lines, including fossil drainage lines.

Mopane is also found on duplex soils, in particular those on sodium-rich granite in areas receiving less than 700 mm of annual rainfall. In areas where mopane is exposed to natural or accelerated soil erosion, it is found as a small tree or a shrub. Although sometimes said to be an indicator of sodic or infertile soils, mopane is by no means confined to them, and indeed grows better on deeper, less compact soils, (Cole, 1986; Henning and White, 1974; Timberlake, 1995). It has been implied that soils under mopane gradually develop a high exchangeable sodium content which inevitably results in reduced permeability and increased susceptibility to erosion (Henning and White, 1974).

Mopane occurs in a range of vegetation types, the structure and associated species depending primarily on soil types and climate. Mopane woodland, savannah and scrubland are often noted for their monotypic stands (Mlambo and Nyathi, 2004; Mlambo, Nyathi and Mapaure, 2005). Where mopane does not form monotypic stands, it is usually found in association with tree species such as *Acacia nigrescens, A. nilotica, Adansonia digitata, Albizia harveyii, Balanites* spp*., Combretum apiculatum, C. hereroense, Commiphora* spp*., Dalbergia melanoxylon, Diospyros quiloensis, Erythrophylum zambesiacum, Kirkia acuminata, Sclerocarya birrea, Terminalia prunoides, T. stuhlmanii,* and *Ziziphus mucronata*. Shrub species include *Combretum elaegnoides, Dichrostachys cineria, Gardenia resiniflua, Grewia* spp., *Ximenia americana*, and species of the family Capparidaceae. The herb layer usually contains species of the Acanthaceae. Grass cover is generally poor and often dominated by annuals such as *Aristida, Enneapogon* and *Eragrostis* species (Cunningham, 1996). Mopane's tolerance of fire and fire-induced "coppicing" are thought to favour its permanent encroachment on perennial grasslands (Henning and White, 1974).

Despite mopane being an important economic tree species, little work has been done on the structure and dynamics of the mopane woodland type when compared to other woodland types. For instance, miombo woodland has been studied in more detail (Chidumayo, 1990). However, among the few studies carried out, Jarman and Thomas (1969) cited in Foloma (2004) found considerable variability in the density of mopane trees in Kariba, Zimbabwe. In Luangwa National Park (Zambia), Lewis (1991) noted different impacts on tree growth and woodland structure as soil characteristics changed. In sites of high nutrient soils, the density of mopane decreased with an increase in elephant browsing while in poor soils mopane did not coppice, hence less browsing, which allowed high survival of younger trees.

2.3.1 Structural growth forms of mopane in Botswana

There are three distinct structural forms of mopane in Botswana, where it occurs as:

- ❖ Mopane woodland with tall and large trees of up to 20 m high, which are usually found in the deep soils in the northern part of the country and on the periphery of the Okavango delta where non-alkaline freely drained sandy soils overlie medium textured sub-soils of higher water holding capacity (Plate 2.4);

- ❖ Mopane savannah with small to medium sized trees usually ranging between 5 and 12 m tall. These trees are mostly found in the north eastern parts of the country (Plate 2.5); and

- ❖ Mopane scrubland with shrubs of up to 3 m high. These are mostly found in the eastern part of the country where non-alkaline freely drained sands do not overlie medium textured sub-soils of higher water holding capacity. The shrub mopane differs from the above two forms in that the bole is not developed, and unlike the mopane trees, they do not produce fruits (Plate 2.6).

Plate 2.4: A typical "cathedral" mopane tree

Plate 2.5: Medium size mopane trees

Plate 2.6: Mopane shrubs

2.4   Distribution of mopane

Mopane is a xeric species of the savannah woodland zone of south tropical Africa, where it is found mostly on heavier-textured soils in wide flat valleys such as the Cunene, Limpopo, Luangwa, Okavango, Shire, and Zambezi (Cole, 1986, Mapaure, 1994; Timberlake, 1995). It is indigenous to southern Africa where it is found in Angola, Botswana, Malawi, Mozambique, Namibia, South Africa, Zambia, and Zimbabwe (Map 2.1). It has also been planted in the semi-arid regions of India where it has shown some success (Timberlake, 1995).

Map 2.1: Natural distribution of mopane in southern Africa (Mapaure, 1994)

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The climatic conditions under which mopane grows vary considerably from areas with summer rainfall to areas with a dry season of about 5-8 months. The mean annual rainfall range for mopane is from 100 to 800 mm. Whereas areas receiving less than 450 mm of rain per annum are considered to be the true ecological niche of mopane (Henning and White, 1974), most mopane woodland is found in the 400-700 mm annual rainfall zones. The mean maximum temperature range of the hottest months is between 34ºC and 38ºC, and the mean minimum temperature of the coldest months is between 12ºC and 16ºC. The species is reported to be intolerant of severe frosts, being restricted by the 5ºC mean daily isotherm for the month of July (Henning and White, 1974; Timberlake, 1995; Van Voorthuizen, 1976).

Mopane is a drought tolerant tree species that, within its natural range, occurs on different habitats that include clay-rich soils such as sites where subsoil has been exposed, termitaria, or drainage lines (including clay pans). The altitude at which mopane is found ranges from 200 m (Mozambique) to 1 500 m (Zimbabwe). The latitude range is between 10ºS and 25ºS (Timberlake, 1995). Mopane occurs on an area covering 550 500 km^2 in southern Africa, of which the proportion per country is shown in Table 2.1

Table 2.1: The area of mopane in its natural range (Mapaure, 1994)

Country	Area (km^2)	Proportion of Country area (%)	Proportion of total mopane area (%)
Angola	112 500	9	20
Botswana	85 000	15	16
Malawi	10 000	9	2
Mozambique	98 000	13	18
Namibia	77 000	9	14
South Africa	23 000	2	4
Zambia	43 500	6	8
Zimbabwe	101 500	26	18
TOTAL	550 500	89	100

NB. Area figures are rounded off to the nearest 500 km^2 or nearest percentage point.

2.4.1 Distribution of mopane in Botswana

Mopane is restricted to the eastern, north, and north eastern parts of Botswana (Map 2.2). Although it is suited to most soil types, it is almost totally absent from the sandveld areas of the Kalahari and Makgadikgadi pans.

DISTRIBUTION OF MOPANE IN BOTSWANA

LEGEND
- Towns/Major Village
- International Boundary
- Major Road
- Major River
- Mopane Distribution
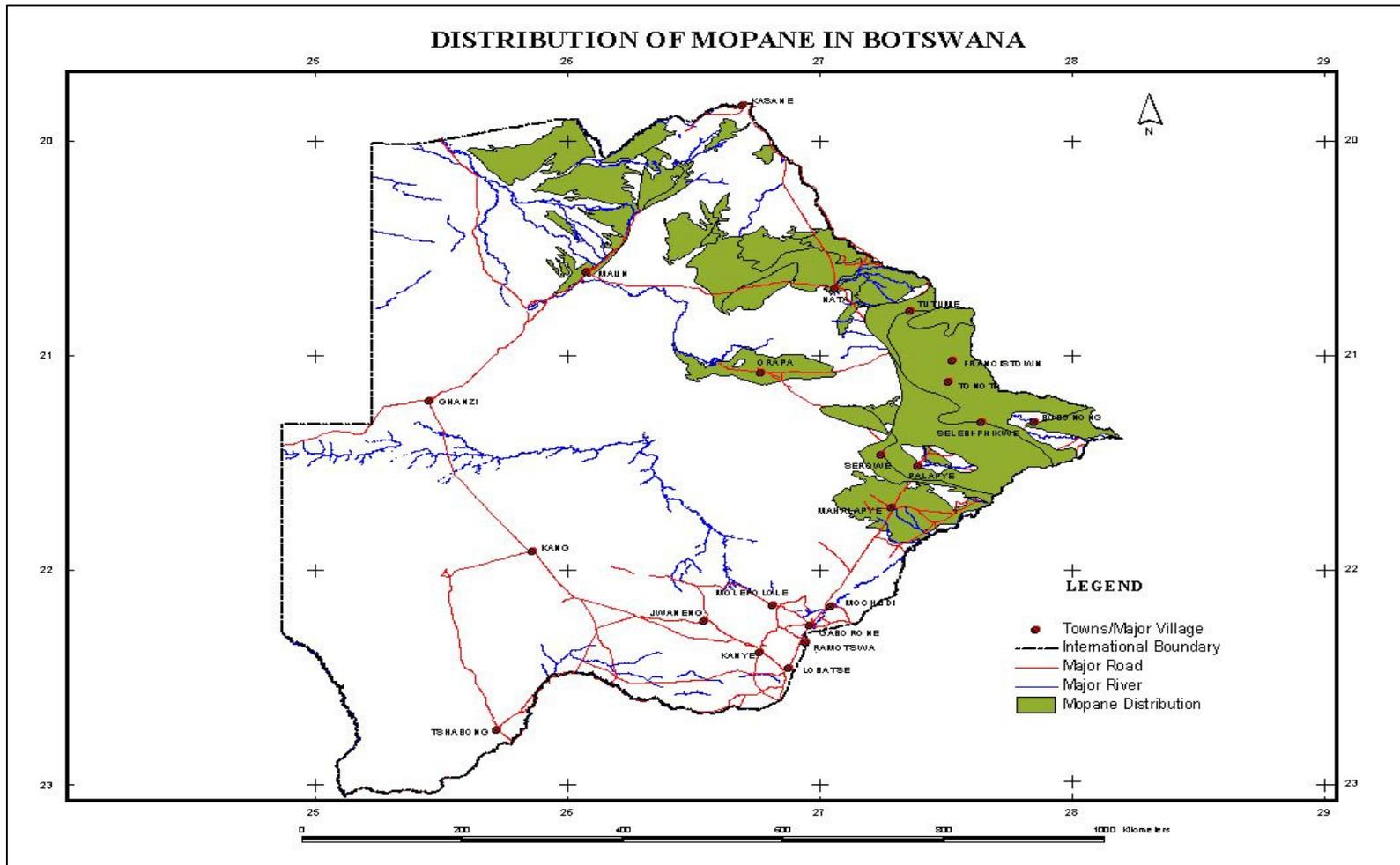
Map 2.2: Natural distribution of mopane in Botswana (Location of Botswana in Africa on Map 1.1) (Weare and Yalala, 1971)

The southern limit of mopane in Botswana is around the 22ºS latitude where *Acacia nigrescens* and *Terminalia sericea* give way to dominance of medium sized mopane trees (Ditlhogo, 1996; Loso, 2003). Its distribution then extends east into Zimbabwe and to the north as far as the Okavango delta and into Namibia (Ditlhogo, 1996; Loso, 2003; Van Voorthuizen, 1976). Soil types and fertility are some of the factors believed to be influencing the limits and growing patterns of mopane.

However, there are a number of individual trees in the southern parts of the country, in Mochudi and Gaborone, about 200 km away from the mopane southern limit. It is not known how these individual trees grew there, but human seed dispersal is believed to be the most likely cause (Loso, 2003). This contravenes the theory of 'frost', which states that the ecological boundaries of mopane are largely controlled by the occurrence of frost.

2.5   Uses of mopane

2.5.1   Wood

Mopane timber is most attractive and durable. The heartwood which is predominantly dark brown with pale blotches is hard, heavy, exceptionally fine textured, and produces a very smooth finish. It has a resinous smell and is resistant to termite attack. The density of the heartwood of mopane is reported to be 1 120 kg/m^3 to 1 280kg/m^3 fresh weight in Zambia; 1 200 kg/m^3 in Zimbabwe, and up to 1 344 kg/m^3 in South Africa, while the wood has 119 g/cm^3 air dry specific weight (Timberlake, 1996). Hence, it is considered a strong, durable, and insect-resistant wood. However, the general specific density, fresh, and air dry weights for mopane are given as 1 041kg/m^3, 1 025kg/m^3, and 897 kg/m^3 respectively (Mopane Technical Information, 2003).

In South Africa, decoctions of the wood are used for treatment against inflammation of the eyes and venereal diseases, specifically against syphilis. The decoction of the wood is also used as a remedy for diarrhoea and dysentery in Zimbabwe. Roots have been used to cure temporary madness in Zambia, and to kill intestinal worms in Mozambique (Timberlake, 1995).

In Namibia, gum extracts from heated wood are used to heal stubborn wounds (Palmer and Pitman, 1972). The wood has a high phosphate and calcium content, while the ash from dry wood contains 15.5% lime and is consequently used as a fertiliser (Palmer and Pitman, 1972; Van der Schijff, 1969). A very strong cord is plaited from its bark.

Although stem form is variable, poles from mopane (Plate 2.7) are mainly used for fencing and hut construction, huts being the widely used form of shelter in many African traditions. Together with poles, stripped bark is used as a rope for hut construction. The wood is also used to make a number of tools and household utensils such as pestles and mortar, milking buckets and mugs.

Commercially, mopane wood has been widely used in southern Africa for pit props, boat building, railway sleepers, and parquet flooring blocks, turnery and bridge piles. In spite of the wood being heavy and hard to work with, pieces of furniture and decorative carvings have been made from the mopane wood. Wood carving for tourist attraction is an income generation activity for some people in southern Africa.

Despite the low burning efficiency of 1.42% for mopane, which was the lowest of eight firewood species that were tested in Botswana (Tietema *et al*., 1991), mopane is a preferred species for firewood (Plate 2.8) in many areas where it occurs because of its quality charcoal. The charcoal gives off intense heat while burning slowly for a long period and it has a moderate ash content of 3.78% of dry weight, with an energy content of 2 170 kJ/kg (Tietema *et al*., 1991).

2.5.2   Browse

In contrast with other species, mopane usually sheds its leaves only after winter, and thus serves as a reliable alternative source of food for both livestock and wild animals during the winter season. In addition, mopane is regarded as a very palatable browse with leaf crude protein levels of 15-18% and neutral detergent insoluble fibre values of 44-57% depending on the leaf age (Macala, 1996). The re-translocation of nutrients from leaves to twigs is slow in mopane. This means that the species retains relatively

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high mineral and protein content throughout the year and is therefore an important source of animal feed (Plate 2.9) during the dry season, and in drought years (Palmer and Pitman, 1972; Skarpe, 1991).

Plate 2.7: Mopane poles for hut construction in Serule

Plate 2.8: Mopane firewood on sale along the Serule-Francistown road

Plate 2.9: Cattle browsing mopane leaves in Serule

Both the fresh leaves from the mopane tree and dry ones from the ground are eaten by livestock and wild animals, and even though the leaves smell strongly of turpentine, the meat and the milk of livestock and wild animals that would have fed on the leaves are not tainted (Palmer and Pitman, 1972; Palgrave, 2002). At a very young stage, the leaves and shoots are utilised by most of the browsers, but when they are fully-grown, it is usually the elephants that use it as a source of nourishment. Normally, the green leaves, twigs, and bark are eaten, but after a forest fire the elephants go from one tree to another breaking off the charred tips of the twigs. Giraffe have also been observed eating this species together with kudu and eland that nibble at the green leaves and young shoots (Lewis, 1991).

2.5.3   Mopane worms

Mopane worms, the larvae of the Emperor moth (*Imbrasia belina*), are commonly known all over southern Africa. They are widespread in southern and tropical Africa (Angola, Botswana, Malawi, Mozambique, Namibia, Zambia and Zimbabwe) (Ditlhogo, 1996). Although these larvae utilise other vegetable matter such as *Sclerocarya birrea* and *Terminalia sericea*, they occur almost exclusively on mopane (Ditlhogo *et al*., 1996). They become 10 cm in length, multi-coloured and exceptionally spiny.

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Sometimes in the summer they are so abundant that they render large patches of mopane trees leafless. These caterpillars are a favourite food to many people who collect, dry and use or sell these worms as additional food (Ditlhogo *et al*., 1996; Gelens, 1996; Van Wyk, 1972).

The palatability of the plant is increased by secretions of an insect (*Arytaina mopane*), the larvae of which subsist on the phloem sap of mopane leaves. The mature insect resembles a miniature cicada while the larva is very small, flat and reddish. Like those of the familiar cuckoo spit insect, these larvae also secrete a fluid, which forms a protective covering from their excretion products called lerp, which cover them later. The lerp consists of a white solid structure, and when the secretions dry out, they form translucent hard "drops" which adhere firmly to the leaves. The lerp is insoluble in water, polar and non-polar solvents, and is covered by a yellow-brownish layer composed predominantly of monosacharrides, fructose and glucose, and contains high potassium and low nitrogen concentrations (Ernst and Sekhwela, 1987). Nowadays, in the northern part of Namibia, this secretion is collected on a large scale and sold commercially on open markets (Gelens, 1996).

2.6 Productivity of mopane

2.6.1 Aboveground biomass

Biomass figures for mature mopane woodland vary greatly because of its occurrence over a wide range of climatic and edaphic conditions. The range of reported biomass figures for mopane in mature woodland is from 1.1 tonnes/ha (fresh weight) in south eastern Zimbabwe to 79 tonnes/ha (fresh weight) in northern Botswana (Tietema, 1989). For mopane shrubland, the reported biomass is 11-18 tonnes/ha (Kelly and Walker, 1976). The aboveground biomass in central Zimbabwe is 68 tonnes/ha (fresh weight), three times the biomass of miombo woodland, of which 95.8% was wood, 4.2% browse (leaves and twigs), while in south eastern Zimbabwe, the aboveground biomass (trees and shrubs combined) ranged from 3.7 to 22.7 tonnes/ha (fresh weight) (Kelly and Walker, 1976).

2.6.2 Belowground biomass

Mopane produces a well-developed tap root system, which grows vertically downwards to a depth of about 1-2 m even though some long tap roots (3 m) of mopane have been dug out in a sandveld in Botswana (Loso, 2003). However, very few studies appear to have been undertaken on belowground biomass, although some data on belowground biomass studies in South Africa are available. Total root biomass in a dense mopane stand of 2 436 plants/ha in northern Transvaal was found to be 29.79 tonnes/ha (fresh weight), with fine roots (0-1 mm) concentrated in the top 20 cms of soil. There was a linear decline with increasing depth (Roux, Smit and Swart, 1994). Coarse roots (>10 cms) showed increased concentration with soil depth up to 40-60 cms, after which they declined (Roux, Smit and Swart, 1994).

In another study, also in the northern Transvaal, the mean total root biomass of a mopane woodland stand was 17.35 tonnes/ha (Smit, Swart and Roux, 1994). Of this, 20% was in the 0-1 mm class, and 20%, 16%, and 44% in the >1-5, >5-10, and >10 mm classes respectively. A mean of 66% of fine roots (<5 mm) was in the top 40 cms of the soil. Coarse roots (>5 mm) were sparse or absent in the top 20 cms, the concentration being highest between 20-60 cm depth. It was estimated that tree roots extended laterally to a distance of 7.6 times the tree height and 12.5 times the canopy width.

2.6.3 Leaf biomass

Mopane leaf biomass is usually considerably lower than root biomass. In the northern Transvaal, the mean leaf biomass was 1.082 tonnes/ha compared with a mean root biomass of 17.354 tonnes/ha (Smit, Swart and Roux, 1994). In southeastern Zimbabwe, the mean leaf biomass, which was found to be 1.6 tonnes/ha (Kelly and Walker, 1976), is also considerably lower than the mean root biomass found in northern Transvaal.

2.7. Allometry and biomass

Relationships between stem, bark, branch, and leaf components can be described through allometric relationships, where *allometry* is the measure and study of the growth or size of a part in relation to an entire organism (Dodge, 2003; Everitt, 1988; Parresol,

1999). Allometric relationships may be used to predict complex tree attributes such as branch biomass or leaf area, from easily measurable attributes such as diameter at breast height, overbark, (*DBH*) or tree height (Dovey, 2005; Dovey, Du Toit and Smith, 2003). In addition, allometric relationships are useful for predicting forest resources (or plantation biomass) (Dovey, Du Toit and Smith, 2003).

The measure and study of the growth or size of a part in relation to an entire organism which was termed *allometry* by Kira and Shidei (1967) or dimensional analysis by Whittaker and Woodwell (1968), is used to predict biomass from destructive sampling and related regression analysis of easily measured tree dimensions such as *DBH*.

It appears that Sir Francis Galton (1822-1911), a well-known British anthropologist and meteorologist, was responsible for the introduction of the word "regression," which he originally used as "reversion" in 1877, but the later term "regression" appeared in his address at Aberdeen in 1885 (Draper and Smith, 1998). Regression is one aspect of correlation analysis which examines two or more variables, i.e. two collections of figures or variables, and establishing to what extent they are related. The dependent variables (also called response variables, explained variables, predicted variables, outputs, or regressands and usually named *y*), are the variables whose values are to be predicted, or explained, given values of the independent variables (also called predictor variables, explanatory variables, control variables, inputs, or regressor and usually named *x*). The primary purpose of correlation analysis is to indicate both the strength and direction the relationship between two measurable variables (Edbon, 1985; Jayaraman, 2000; Johnson, 1988). There are different measures of correlation, but the most generally used is one called the *Pearson's product moment correlation coefficient* or simply *correlation coefficient*, commonly symbolised as *r* and derived using the following equation (Edbon, 1985; Jayaraman, 2000; Johnson, 1988):

$$r = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}}$$
(2.1)

Where:

x = values of the independent variables

y = values of the dependent variables

$\bar{x}$ and $\bar{y}$ = respective means of the two sets of variables

The product moment correlation coefficient only measures the strength and direction of the relationship between two variables, but not the form of that relationship. The form is assumed to be linear. The sample correlation coefficient is denoted by r, and the population correlation coefficient by ρ. The range of r or ρ is from -1 to +1 and does not carry any unit. When its value is zero, it means that there is no linear relationship between the variables concerned, although a low correlation coefficient does not necessarily mean a low degree of association. The relationship may be very high, but curvilinear, and this would not be indicated by the coefficient. A strong linear relationship exists when the value of r approaches -1 or +1. A negative value of r is an indication that an increase in the value of one variable is associated with a decrease in the value of the other. A positive value on the other hand, indicates a direct relationship.

A value of correlation obtained from a sample needs to be tested for significance to confirm if a real relationship exists between the two variables in the population considered. It is usual to set up the null hypothesis as $H_0 : \rho = 0$ against the alternative hypothesis $H_1 : \rho \neq 0$ for a two-tailed test and either $H_1 : \rho > 0$ or $H_1 : \rho < 0$ for a one-tailed test. For relatively small n, the null hypothesis that $\rho = 0$ can be tested using the test statistic:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \tag{2.2}$$

Where:

n = number of variables

r = correlation coefficient

Regression analysis is used to model relationships between random variables, determine the magnitude of the relationships between variables, and can be used to make predictions based on the models. It models the relationship between one or more response variables and the predictor variables. In problems that deal with correlation and regression analysis, the sample data are usually presented pictorially on a scatter diagram. A scatter diagram is a plot of all the ordered pairs of *bivariate* data on a coordinate axis system. The independent variable x is plotted on the horizontal axis while the dependent variable y is plotted on the vertical axis.

Simple linear regression and multiple linear regression model the relationship between two or more variables using a linear equation. Simple linear regression refers to the treatment of one dependent and one independent variable and is of the form:

$$y = \beta_0 + \beta_1 x \tag{2.3}$$

Where:

y = estimated value of the dependent variable

x = value of the independent variable

β_0 = an estimate of the intercept of the regression line

β_1 = an estimate of the slope of the regression line

Multiple regression refers to a regression on two or more variables and its model is as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots \beta_k x_k \tag{2.4}$$

Where:

y = value of the dependent variable

x = value of the independent variable

β_0 = an estimate of the intercept of the regression line

$\beta_1, \beta_2 \ldots \beta_k$ = regression coefficients

Linear regression assumes that the best estimate of the response is a linear function of some parameters (though not necessarily linear on the predictors). If the relationship between the variables being analysed is not linear in parameters, a number of non-linear regression techniques such as the quadratic or exponential equations may be used to obtain a more accurate regression. The knowledge of the relationship enables the prediction and control of events. For example, if there is a close relationship between seed germination and the amount of seeds, it is possible to predict how many seeds will be required to attain a given seed germination percentage.

The relationship between the variables is expressed as an equation for a line (regression line) or curve (regression curve) in which any coefficient (regression coefficient) of the independent variable in the equation has been determined from a sample population. First, an equation to express the relationship between the two variables is sought, and the equation that is chosen is the one that *best fits* the scatter diagram. Below are some examples of prediction equations:

The essential part of regression analysis is the calculation of the equation of the line of best fit which is determined by its y-intercept (β_0) and its slope (β_1).

$$\beta_0 = \frac{1}{n}\left(\sum y - b_1 \cdot \sum x\right) \tag{2.5}$$

$$\beta_1 = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sum (x-\bar{x})^2} \tag{2.6}$$

Where:

x = value of the independent variables

y = value of dependent variables

n = number of variables

$\bar{x}$ and $\bar{y}$ = respective means of the two sets of variables

There has been an increased utilization of biomass as a unit of measure in forestry. Weight tables for many forest tree species are available, and forest yields have been

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estimated in terms of weight or biomass (Crow, 1978). The estimation of biomass or volume of trees and shrubs is important in many contexts in most parts of the world. It may be of interest in purely environmental studies, or it may be required in connection with studies of potential supply of both industrial wood and biomass for domestic energy, and it will be an element in all attempts at sustainable management of forests and woodland ecosystems.

Many such biomass models calculated by regression analysis, which are in most cases developed for specific applications, are now in existence. These models have the same objective: to evaluate some difficult-to-measure tree characteristics from easily measurable tree attributes such as *DBH*, total height, or tree age. Generally, the models are exponential, hyperbolic or linear (Saint-André *et al*., 2005).

Biomass content can be measured through direct or indirect methods. The direct (destructive) method consists of harvesting the tree to determine biomass through the actual weight of each of its components, for example roots, stem, branches, and foliage (Parresol, 1999). This information is then used to estimate individual tree biomass using mathematical models, frequently through regression analysis.

The indirect method is usually used when the tree has large dimensions, which is the case in natural tropical forests. In this case, tree dimensions are measured, and the volume of the stem and larger branches may be calculated, depending on the measurements available, by using one of the formulae given in Table 2.2 (Bredenkamp, 2000; Jayaraman, 2000; Segura and Kanninen, 2005). This information is then used to determine the specific weight, which is calculated from the ratio between the calculated volume of the tree components and their weight (Tietema *et al*., 1991).

Table 2.2: Some formulae for calculating the volume of a log

Formula	Name
$V = d_{1/2}^2 \times \pi \div 4 \times l$	Huber's formula
$V = (d_t^2 + d_T^2) \times \pi \div 8 \times l$	Smalian's formula
$V = (d_t^2 + 4d_{1/2}^2 + d_T^2) \times \pi \div 24 \times l$	Newton's formula

Where:

V = volume of a log

l = length of a log

d = diameter of a log

$d_{1/2}$ = diameter at mid-length of a log

d_t = diameter at thin end of a log

d_T = diameter at thick end of a log

The most commonly used is Huber's method, which is slightly more accurate than Smalian's method, which is easier to use when under-bark volume is required. Newton's method, which is the most accurate, is more time-consuming (Bredenkamp, 2000).

Other options involve the measurement of parameters related to stands, vegetation types or even pixels in satellite images in order to estimate the biomass of vegetation in broad categories of land (Hofstad, 2005), and the estimation of biomass based on a computerized evaluation of tree bio-volume (Montès *et al.*, 2000).

Although weighing the actual tree biomass in the field is undoubtedly the most accurate method to determine tree biomass, it is generally a time consuming and destructive method that is usually restricted to small areas and small tree sample sizes (Xiao and Ceulemans, 2004). Therefore, the use of allometric relationships which yield a non-destructive and indirect measurement of biomass compartments is often the preferred approach since it is less time consuming and less expensive than direct measurements (Crow, 1978; Montès *et al.*, 2000; Parresol, 1999; Xiao and Ceulemans, 2004).

Even though the use of predictive models derived from allometric relationships is the preferred approach to determine tree biomass, the models have been found to vary from species to species, and for a given species, from stand to stand (Jayaraman, 2000). Furthermore, the models may not be accurate in the case of individual trees, but have been found to work well when applied repeatedly on several trees and the results aggregated such as in the computation of stand volume (Jayaraman, 2000). Whenever an appropriate model is not available, a new prediction model will have to be established. This will involve the determination of actual biomass of a sample set of trees and relating them to non-destructive measures like *DBH* and tree height through regression analysis.

Researchers have used a variety of regression models for estimating total-tree and tree-component biomass, and the following three forms have generally been used to develop predictive regression equations (Parresol, 1999):

Linear (additive error): $y = \beta_o + \beta_1 x_1 + \cdots \beta_k x_k + \in$ (2.7)

Nonlinear (additive error): $y = \beta_o x_1^{b_1} x_2^{b_2} \cdots x_k^{b_k} + \in$ (2.8)

Nonlinear (multiplicative): $y = \beta_o x_1^{b_1} x_2^{b_2} \cdots x_k^{b_k} \in$ (2.9)

Where:

y = value of the dependent variable

β_0 = an estimate of the intercept of the regression line

b_k = model parameter

$\in$ = error term

β_1, β_k = estimate of the slope of the regression line

$x_1, x_2 \cdots x_k$ = values of the independent variables

However, the most common mathematical model in tree volume studies is one of the form $y = \beta x^b$ (Xiao and Ceulemans, 2004; Zianis and Mencuccini, 2004). For example, in a tree volume study in northern Botswana, the volume model derived using *DBH* as a

prediction variable was found to be $y = 0.0001065x^{2.471}$ with an R^2 of 0.95 from n = 36 (Tietema, 1993). The power curves were also found to be the best prediction models for other species such as *Julbernardia globiflora* and *Pterocarpus angolensis* in Tanzania (Malimbwi, Solberg and Luoga 1994). The biomass prediction models that have been developed for mopane in some southern African countries are shown in Table 2.3 (Timberlake, 1995).

Table 2.3: Biomass prediction models for mopane and other tree species in southern Africa

Study	Species	DBH (cm)	Model*	n	R^2 (%)
Chamshama, Mugasha and Zahabu (2004)	Miombo woodland species (Tanzania)	1-57	$\ln B = 0.01559 + 2.796 \ln DBH$	30	97
Chamshama, Mugasha and Zahabu (2004)	Miombo woodland species (Tanzania)	1-57	$\ln B = 0.0263 + 1.505 \ln DBH + 1.762 \ln H$	30	98
Chamshama, Mugasha and Zahabu (2004)	Miombo woodland species (Tanzania)	1-57	$B = -47.86 + 0.3813 DBH^2$	30	82
Chamshama, Mugasha and Zahabu (2004)	Miombo woodland species (Tanzania)	1-57	$B = 49.73 + 0.3793 DBH^2 + 0.381 H$	30	83
Chidumayo (1990)	Various miombo species (Zambia)	<10	$B = 1.6 DSH - 4$	7	94
Grundy (1995)	*Brachystegia spiciformis* (Zimbabwe)	2-25	$\log_{10} B = 2.46 + 1.04 \log_{10} \sum (d^2)L)$	132	97
Grundy (1995)	*Julbernardia globiflora* (Zimbabwe)	1.4-25.8	$\log_{10} B = 2.46 + 1.04 \log_{10} \sum (d^2)L)$	140	98
Malimbwi, Solberg and Luoga (1994)	Various miombo species (Tanzania)	>5	$B = 0.06 DBH^{2.012} H^{0.7}$	17	95
Stromgaard (1985)	Various miombo species (Zambia)	2-70	$\ln B = -0.739 + 0.890 \ln DBH + 0.132 \ln H - 0.103 \ln H^2$	271	72
Tietema (1993)	Various woodland species (Botswana)	2-36 (DSH)	$B = 0.1936 BA^{1.1654}$	512	92
Tietema (1993)	*Colophospermum mopane* (Botswana)	2-36	$B = 0.0644 BA^{1.3341}$	36	95

*Note: B = biomass (kg); BA = basal area (cm^2); d = diameter (cm); DBH (cm); DSH = diameter at stump height (cm); H = height (m); L = stem length (m)

A comparison of the models developed in this study with those of other workers (Table 2.3) show that different variables have been used in each case. The model developed by Stromgaard (1985) in Zambian miombo, use *DBH* and total height of tree. Chidumayo (1990), also working in mixed Zambian miombo, developed another set of linear functions for mixed miombo, using diameters at stump height (30 cm), which accounted for most of the variation in wood biomass. Shackleton (2002) used the stem circumference which was found to be positively correlated to total tree mass of *Pterocarpus angolensis* in the savannahs of the South African lowveld. Unfortunately the data used by Tietema (1993) were not available for inclusion in this study.

3.   MATERIALS AND METHODS

3.1   Introduction

This chapter comprises descriptions of the study sites, materials, and field and laboratory methods used to obtain data in this study.

3.2   Study sites

The three study sites of Serule, Sexaxa, and Tamacha are located in Botswana (Map 3.1) and were selected in terms of their annual total rainfall and annual mean temperature ranges as described below. The study sites have slightly different soil types. The soil group in Serule is composed of small units of *regosols* and *leptosols* on hillcrests and upper slopes while the lower slopes comprise larger scale units of *lixisols* and/or *chromic luvisols*. On the other hand, the predominant soils in Sexaxa and Tamacha are the *eutric arenosols*. The soil groups in the study areas and their description are shown in Table 3.1. The presence among the dominant woody species of the economically important mopane was also critical in the site selection in order to allow comparison between the study sites. The description of each study site follows, in terms of major land features, vegetation types and dominant woody plant species.

3.2.1   Serule

Serule (21º56'S 27º31'E), which is located along the main north-south A1 road in the densely populated north-eastern part of Botswana, lies at an altitude of 892 metres above sea level. The rainfall figures for Serule over 30 years (1970-2000) are not available; hence it is only the total annual rainfall over the previous 5 years (2001-2005) that is shown in Figure 3.1 (Anon., 2006). The average rainfall over the same period (2001-2005) for Serule is 367 mm with 30% variability. The annual mean maximum and minimum temperature figures over 30 years (1970-2000) for Serule are not available; hence Figures 3.2 and 3.3 only show the annual mean maximum and minimum temperatures respectively for the study site over the previous 5 years (2001-2005) (Anon., 2006).

LOCATION OF STUDY SITES

LEGEND

- Towns/Major Village
- Study Sites
- International Boundary
- Major Road
- Major River
- Mopane Distribution
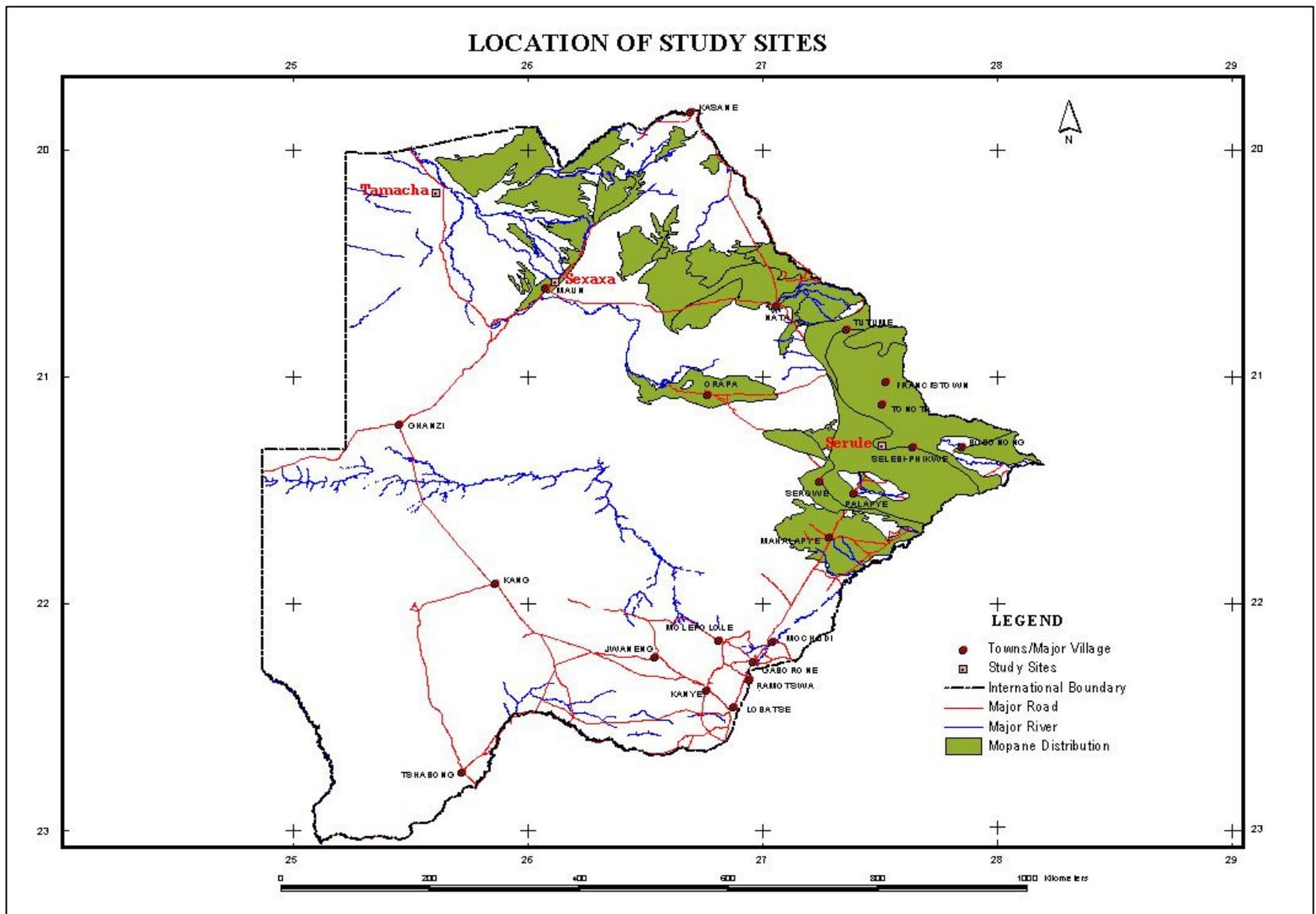
Map 3.1: Location of study sites

Table 3.1: Soil groups found in the study sites and their description (FAO, 1990)

Soil group	Description
Eutric Arenosol	The typical Kalahari sands which are often deep to very deep, weakly developed coarse textured and unstructured soils which are coarser than sandy loams in the top 100 cm. They are poorly to imperfectly drained, dark greyish brown to black sandy loams.
Leptosol	Soils which are limited in depth by rocks or calcareous layer (weakly developed shallow soils).
Lixisol	Soils with an accumulation of clay, subject to strong weathering. They are derived from alluvial soils with an increasing clay content but weak soil structure down the profile. They tend to coarse sandy loam soils, and loamy sands of low fertility.
Chromic Luvisol	Soils with an accumulation of clay. They are derived from alluvial soils with an increasing clay content and soil structure down the profile. They tend to be moderately deep to very deep, moderately well to slightly excessively drained strong to dark red fine sandy loam, or sandy clay loam soils of moderate fertility.
Regosol	Shallow soils derived from unconsolidated parent materials. They have no diagnostic horizons.
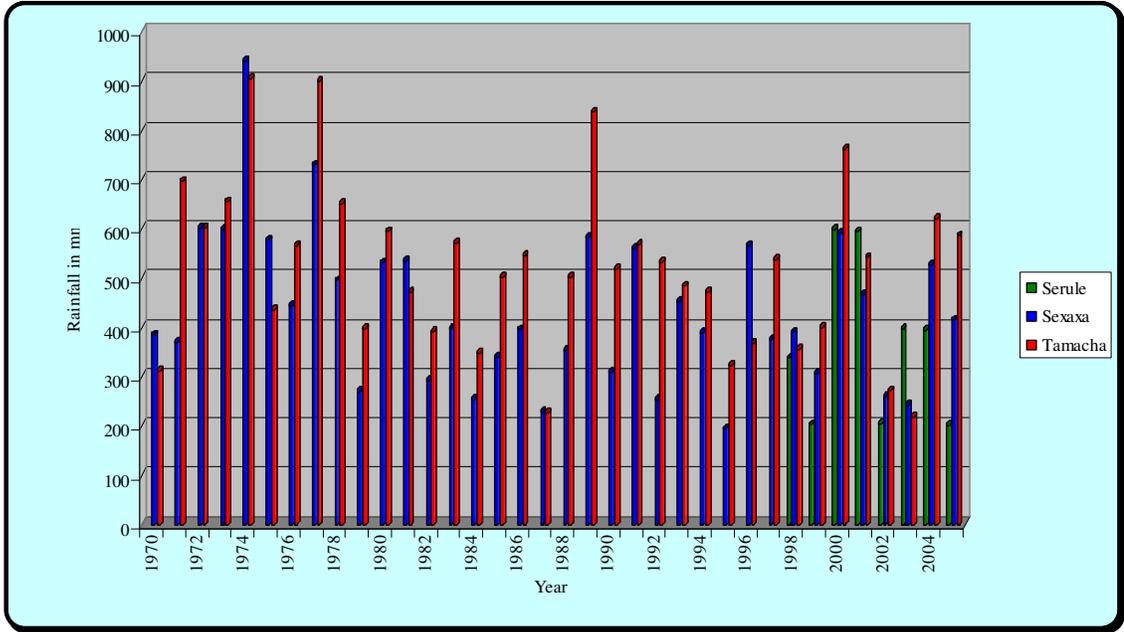
Figure 3.1: Total annual rainfall for the study sites (1970-2005)
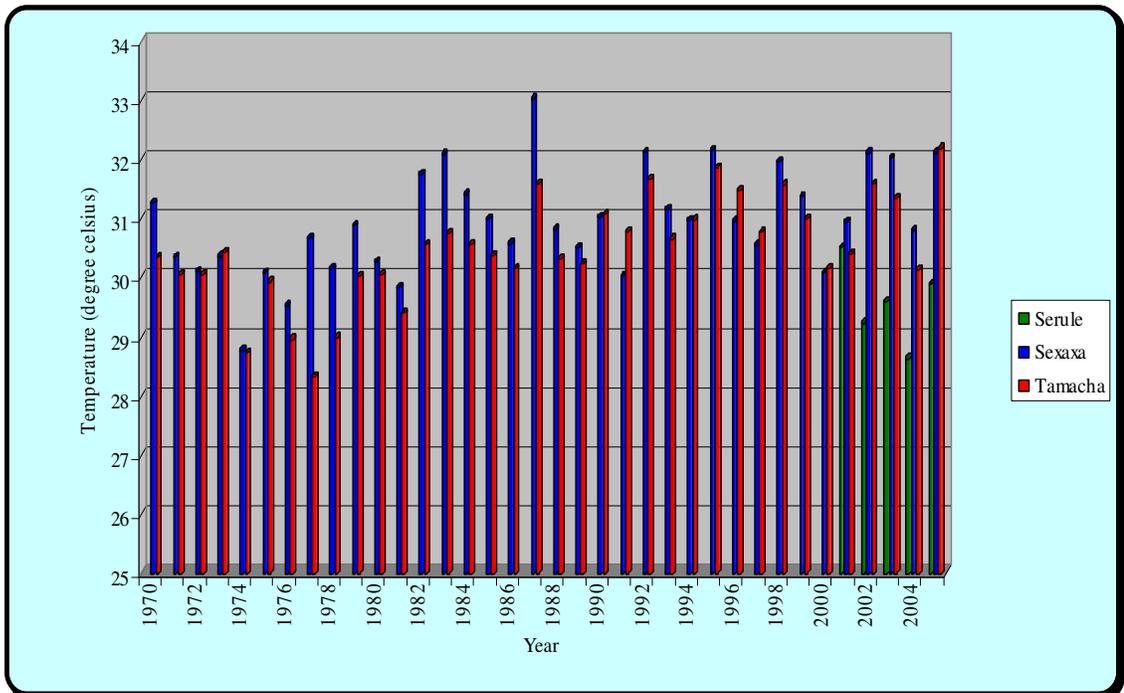
Figure 3.2: Mean annual maximum temperature for the study sites (1970-2005)
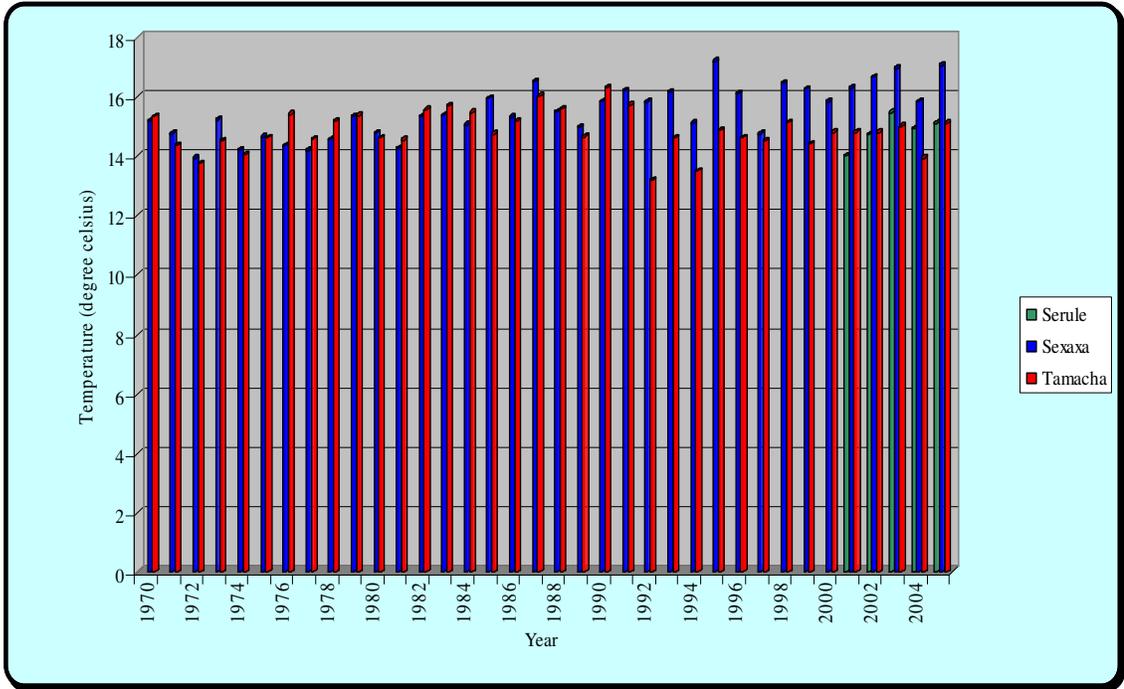
Figure 3.3: Mean annual minimum temperature for the study sites (1970-2005)

The vegetation that occurs in Serule is dominated by mopane scrub (Plate 3.1). In addition to the mopane scrub, other principal woody plant species are *Acacia tortilis*, *A. nigrescens*, *Combretum apiculatum*, *Dichrostachys cineria* and *Kirkia acuminata*.

Plate 3.1: Mopane scrub in Serule

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3.2.2 Sexaxa

The Sexaxa site (29º09'S 23º46'E), which is situated 15 km north of Maun in north-western Botswana, lies at an altitude of 945 metres above sea level. The average rainfall over 35 years (1970-2005) for Sexaxa is 435 mm with 30% variability, while the total annual rainfall for the same period is shown in Figure 3.1 (Anon., 2006). The annual mean maximum and minimum temperatures over 35 years (1970-2005) for Sexaxa are shown in Figures 3.2 and 3.3 respectively (Anon., 2006).

The predominant natural vegetation in Sexaxa is deciduous savannah woodland that varies from shrub/bush to tree layers, sometimes forming a dense canopy. The principal woody species in Sexaxa is mopane (Plate 3.2), which is found in association with *Acacia erioloba, A. luederitzii, A. mellifera* and *Terminalia sericea.*

Plate 3.2: Mopane woodland in Sexaxa

3.2.3 Tamacha

Tamacha is located outside the fringes of the Okavango Delta (18º48'S 22º04'E) in the extreme north-western Botswana at an altitude of 1 023 metres above sea level. The average rainfall over 35 years (1970-2005) for Tamacha is 519 mm with 30%

variability, while the total annual rainfall for the same period is shown in Figure 3.1 (Anon., 2006). The annual mean maximum and minimum temperatures over 35 years (1970-2005) for Tamacha are shown in Figures 3.2 and 3.3 respectively (Anon., 2006).

The dominant woody vegetation layer in Tamacha varies from shrub to open forest with tall and mostly single stemmed mopane trees that almost form monotypic woodland (Plate 3.3). Other woody species found in Tamacha are *Baikiaea plurijuga*, *Burkea africana* and *Pterocarpus angolensis*, all of which are valuable timber species. The map by Weare and Yalala (1971) shown in Figure 3.1 does not show that the Tamacha site falls within the natural range of mopane in Botswana. However, the map is used in this study because it is the only available current map in Botswana that shows the distribution of mopane in Botswana.

Plate 3.3: Mopane woodland in Tamacha

3.3 Sampling

At each of the study sites, stratified random sampling procedures were applied, and a sample of thirty[2] (30) trees was selected per site, stratified within the stem diameter classes of each study site. Natural forests such as those found in the study sites are uneven-aged and therefore highly variable. Therefore, in such natural forests, large samples would usually be required to attain an accurate estimate of the correlation with the population from which the samples were taken. Nevertheless, predictions of mopane biomass from a few sample trees could be more accurate than in most natural woodland types because mopane woodland is usually composed of even-sized stands that generally make up 90% of the total biomass, with only 3-7% of total mopane biomass being browse (leaves and twigs) (Timberlake, 1996).

The stem diameter strata of the study sites were determined from the data collected from permanent sample plots previously laid out on the study sites for vegetation studies by Kemoreile, Sekhwela and Mutakela (2004) and Mutakela, Sekhwela and Kemoreile (2004). The *DBH* of all mopane trees in each permanent sample plot were measured and the trees were classified according to their respective diameter classes. Thus, at each of the study sites, five mopane sample trees were randomly selected for felling from each of the following six (6) *DBH* classes: Class 1 ($\geq$ 25.1 cm); Class 2 (20.1 – 25.0 cm); Class 3 (15.1 – 20.0 cm); Class 4 (10.1 – 15.0 cm); Class 5 (5.1 – 10.0 cm); and Class 6 ($\leq$ 5.0 cm).

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[2] Severe transport and manpower constraints were encountered when collecting field data for this study, as the author had limited access to the use of an official four-wheel drive vehicle and manpower which were provided by the Department of Forestry and Range Resources (DFRR) in Botswana. As a result, it was only possible to fell 30 sample trees at each study site.

3.4   Baseline data

The stem diameters for all the sample trees were measured at 0.15 m from the ground; 1.3 m from the ground and at 3 m from the ground. The crown diameter and total tree height for each of the sample trees were also measured.   The crown diameter was measured at two perpendicular axes. The longest axis of the crown diameter and the axis perpendicular to the longest axis were measured. The average of the two measurements was taken as the crown diameter measurement.

The crown diameter was measured using a 50 m measuring tape (Plate 3.4) while diameter tapes were used for measuring the *DBH*, and stem diameter at 0.15 m. While the stem diameter at 0.15 m may be difficult to measure in coniferous plantations because of litter accumulation on the ground, it is fairly easy in mopane woodlands because there is usually very little litter accumulation on the ground. The stem diameter at 3 m was measured using a Finnish calliper, while the total tree height was measured using a *Haga* hypsometer for trees over 5 m tall and a 5 m telescopic measuring pole for trees/shrubs less than 5 m tall. All data were recorded on a clearly labelled data sheet, an example of which is attached as an appendix I.

Plate 3.4: The author and a colleague measuring crown diameter
(Photo: Bernard Phillemon)

3.5   Biomass data

After measuring the baseline data of the sample trees, the trees were felled to determine their fresh weight. They were cut at 15 cm from the ground using a chainsaw. Each felled sample tree was partitioned into crown (leaves, twigs, and small branches with a branch butt diameter ≤ 2 cm); large branches (branch butt diameter ≥ 2.1 cm); and stem. These methods are similar to those described by Bernardo *et al*. (1998); Chamshama *et al*. (2004); Chidumayo (1990); and Fuwape, Onyekwelu and Adekunle (2001). The total length of the stem was measured up to 2 cm top diameter and the part smaller than 2 cm was included as crown (Bernardo *et al*., 1998). The middle diameter of the stem and its utilizable length were then measured before the stem was cross-cut into 1 m billets for biomass determination. A diameter tape and a 50 m measuring tape were used for measuring the stem middle diameter and utilizable length respectively. The utilizable stem length was considered as the straight part of the stem that could be used as poles or building rafters. The length of each branch and its utilizable length, if any, were also similarly measured.

The stem and branch components were then cross-cut into 1 m billets, each of which was weighed to determine its fresh weight using a 100 kg spring-dial hoist scale balance mounted on a neighbouring tree (Plate 3.5). Thereafter, the total fresh weight of each sample tree was calculated by summing the fresh weights of the components.

Plate 3.5: Weighing stem billets

3.6   Sampling for oven-dry weight determination

In order to reduce bias when randomly selecting a sample tree for oven-dry weight determination, the five sample trees in each diameter class were numbered from 1-5 and the five numbers representing the sample trees were placed in a cotton bag after which one number was drawn from the cotton bag. The samples for oven-dry weight determination were collected from the sample tree represented by the drawn number.

One wood disc sample of about 2 cm thick (Chamshama *et al*., 2004) was cut from the stem at 0.15 m, 1.3 m and at the top diameter (2 cm) of a randomly selected stem in each

diameter class. Each wood disc sample was immediately weighed on a 5 kg kitchen scale to determine its fresh weight (Plate 3.6).

Plate 3.6: The author weighing a wood disc in the field
(Photo: Obuile Tlhokwane)

A further sample of three wood discs (2 cm thick each) was randomly selected and cut from the branches (≥ 2 cm butt diameter) of the randomly selected sample tree. All the branches of the sample tree were numbered, after which the numbers were placed in a cotton bag. Three numbers were then successively drawn from the cotton bag without replacement of the drawn number so that one number stood only one chance of being drawn. Wood discs were cut from the branches represented by the randomly drawn numbers. The wood discs were weighed on a 5 kg kitchen scale to determine their fresh weight.

From the crown, a sample of four twigs (15 cm length) from the small branches (≤ 2 cm butt diameter) were selected in such a way that they represented the largest and the

smallest twigs (one each) and two from the intermediate branch sizes (Chidumayo, 1990; Fuwape *et al*., 2001). The random selection of these samples was done by measuring the butt diameters of all the branches to determine the range of the butt diameter distribution. The branches were then divided into three diameter classes that represented the largest, intermediate, and small branches. All the branches in each diameter class were numbered, after which all the numbers that represented the branches from each diameter class were placed in one cotton bag, such that there were three cotton bags for the three branch diameter classes. Thereafter, one number was drawn from each of the two cotton bags that contained the numbers for the largest and smallest branches, while for the intermediate sized branches, two numbers were successively drawn without replacement of the drawn number. The fresh weight of the wood discs was determined by weighing on a 5 kg kitchen scale.

The fresh weight of the leaves of the sample tree was determined by filling a 2 litre bucket with uncompressed fresh leaves that were collected from the sample tree. The leaves were then transferred to a cotton bag and their weight was determined using a 5 kg kitchen scale. A leaf was considered to be fresh when the whole leaf was completely green and did not have any patches of discolouration.

After the fresh weight of the samples was determined and recorded, the samples were placed in labelled cotton bags and taken to the laboratory for moisture determination.

3.7   Moisture content determination

In the laboratory, the initial fresh weight of all the samples from the stem, branches, and crown was taken before the samples were placed in Manila drying paper for drying in an oven at 90ºC (Chamshama *et al*., 2004; Fuwape *et al*., 2001; Sekhwela, 2000) until constant dry weight was attained. Wood (stem and branch) samples were cut into small pieces and the fresh weight of the individual smaller samples recorded before being dried to determine their oven dry weight. The samples were weighed every 24 hours. To reduce moisture re-absorption by the samples when they were removed from the oven for re-weighing, the samples were placed in a desiccator containing silica gel.

The moisture content of the component samples was computed as follows:

$$mc = \frac{fws - dws}{fws} x100\%$$ (3.1)

Where:

       mc = moisture content

     fws = fresh weight of the component sample

    dws = dry weight of the component sample

The total dry weight of the sample tree was then calculated by applying the ratio of fresh weight to dry weight observed in the sample tree to the corresponding total fresh weight of the component parts, such that:

$$tdw = \frac{dws}{fws}(tfw)$$ (3.2)

Where:

     tdw = total dry weight of sample tree

    dws = total dry weight of component sample

     fws = total fresh weight of component sample

     tfw = total fresh weight of sample tree

3.8 Data analysis

The collected data were statistically analysed using the Minitab® Release 14 statistical software (Minitab Inc., 2003). The collected data (stem diameter at 0.15 m; stem diameter at 1.3 m; stem diameter at 3.0 m; crown diameter; total tree height; and total tree aboveground biomass) were all transformed to their natural logarithms in an attempt to reduce heteroscedasticity[3] often associated with most volume or biomass data (Philip, 1994).

A natural logarithm function tends to squeeze together the larger values in the data set and stretches out the smaller values. The squeezing and stretching can correct one or more of the following problems in the data:

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[3] One of the assumptions of regression and/or Analysis of Variance (ANOVA) is that the variance of the error term should be constant. Thus, heteroscedasticity refers to the inconstant variance of the error term.

a) inconstant variance;

b) outliers; and

c) skewed data

The regression and Analysis of Variance (ANOVA) procedures make the following assumptions about the residual errors:

i)   Errors are normally distributed with mean zero;

ii)   The error variance does not change for different levels of a factor, or according to the values of the predicted response; and

iii)   Each error is independent of all other errors.

The validity of these assumptions was checked in the statistical analysis. The normal distribution was tested using the Anderson-Darling test for normality while the error variance was tested using the Bartlett's and Levene's tests for equal variance.

3.8.1   Criteria for goodness of fit and predictive ability

During the regression analysis, the coefficient of determination (R^2) and mean square error (*MSE*) were calculated and they were used to determine the goodness of fit. However, these statistics were used with caution because models with different dependent and independent variables and with different numbers of estimated parameters cannot readily be compared.

In order to compare the predictive ability of the different models, the percentage of the bias and standard error of estimate (*SEE*) were calculated. The bias and *SEE* percentage values are reported in terms of the real dependent variables and not in terms of the transformed dependent variables used in the regression analysis.

The percentage bias was calculated as follows:

$$B(\%) = \frac{1}{n} \left[\sum_{i=1}^{n} \frac{(Y_i - \hat{Y}_i)}{Y_i} \right] x\ 100 \qquad (3.3)$$

Where:

$B(\%)$ = percentage bias

Y_i = observed value

$\hat{Y}_i$ = predicted value

n = number of observations

The *SEE* is the square root of the variance and gives an indication of the spread of the actual observations (Y_i) around the predicted values ($\hat{Y}_i$). The *SEE* can be expressed as a percentage as follows:

$$SEE(\%) = \left[\sqrt{\frac{\sum_{i=1}^{n}\left(\frac{Y_i - \hat{Y}_i}{Y_i}\right)^2}{n-q}} \right] \; x \; 100 \qquad (3.4)$$

Where:

$SEE(\%)$ = percentage standard error of estimate

Y_i = observed value

$\hat{Y}_i$ = predicted value

n = number of observations

q = number of parameters used in the estimation

The plots of the predicted and residual values were visually inspected to determine if there was any pattern that could indicate violation of regression assumptions. The influence of observations was verified using the following diagnostic tests:

a) The standardized residual is a measure of the distance of each observation from the regression line. An unusually large residual indicates that the data point is an outlier (in the vertical direction) and that it could be influential. The Minitab®

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statistical package classifies any observation with a studentized residual greater than 2 as an outlier.

b) Leverage also called *HI* in the Minitab® statistical package is a measure of how far an independent variable deviates from its mean. An observation with an extreme value on a predictor variable is called a point with a high leverage. Generally an observation with leverage greater than $\left|\dfrac{2p'}{n}\right|$ should be carefully examined.

Where:

p' = number of parameters in the model

n = number of data points in the regression

c) *Cook's D* measures the change to the estimates that results from deleting each observation. It is very similar to *DFFits*. An observation with *Cook's D_k* greater than $\left|\dfrac{4}{n}\right|$ has an influence on the estimated value of b_k.

Where:

n = number of data points in the regression

d) *DFFits* are scaled measure of the change in the predicted value for the *i*th observation and are calculated by deleting the *i*th observation. An observation with *DFFits_k* greater than $\left|2\sqrt{\dfrac{p'}{n}}\right|$ has an influence on the estimated value of b_k.

Where:

p' = number of parameters in the model

n = number of data points in the regression

e) *DFbetas* are the scaled measure of the change in each parameter estimate and are calculated by deleting the *i*th observation. An observation with $DFbetas_k$ greater than $\left|\dfrac{2}{\sqrt{n}}\right|$ has an influence on the estimated value of b_k.

Where:

n = number of data points in the regression

3.9   Limitations to field work

The study sites are far apart. There is an average of 500 km between the three study sites, with Tamacha being approximately 1 000 km away from the city of Gaborone (The author's duty station). A lot of time was taken travelling from one study site to another. This severely reduced the total number of days that could be used in the actual data collection, because the official four-wheel drive vehicle and manpower used in this study were allocated for a limited period of two weeks.

4.   RESULTS and DISCUSSION

4.1   Sample data

4.1.1   Distribution of sample trees

The range of *DBH* sizes for the sampled trees is shown in Figure 4.1. Although there are distinct differences between the growing sites, it is clear that the data from the sampled sites in Figure 4.1 follow a similar *DBH*-total tree aboveground biomass trend and appear like samples from a single population. This *DBH*-total tree aboveground biomass trend shows that irrespective of site, the stem diameter of mopane is positively correlated to total biomass. This was to be expected because generally tree biomass or volume increases with increased stem diameter.
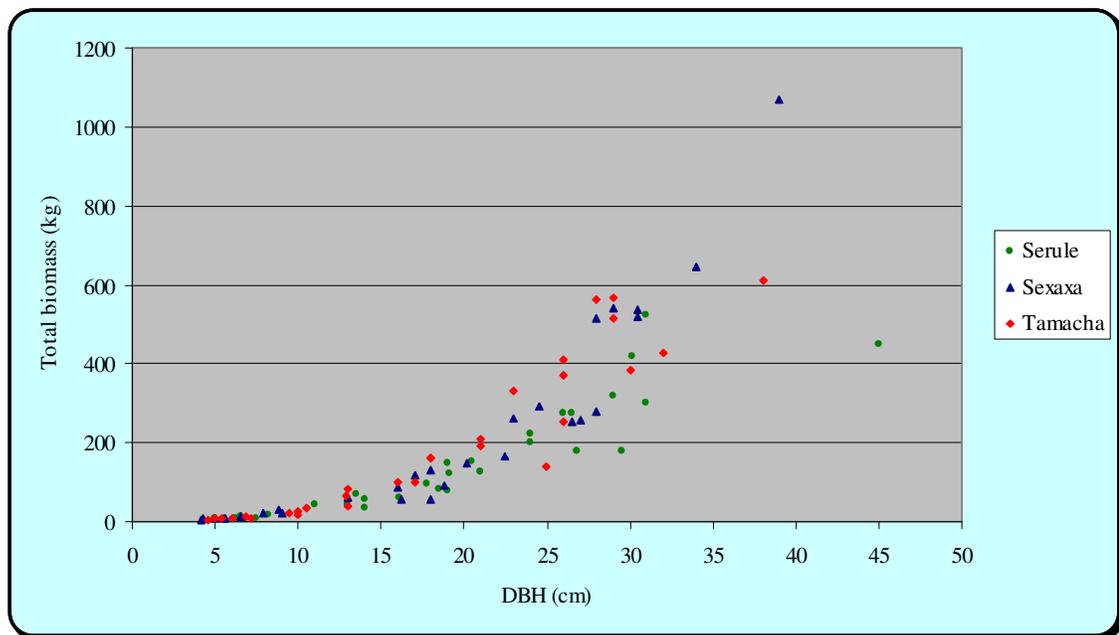
Figure 4.1: Distribution of sample trees across the *DBH*-total tree aboveground biomass range

Furthermore, Figure 4.1 shows that there appears to be very little variability in the *DBH* measurements of the sample trees across the three sites. This may be because the assumptions of random sampling were deliberately violated by possibly introducing

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personal bias through the subjective selection of the sample trees to fit the prescribed *DBH* classes.

4.1.2 Mean tree height

The mean tree height for the sample trees per DBH class was found to be higher at Tamacha followed by Sexaxa and lastly Serule (Figure 4.2).
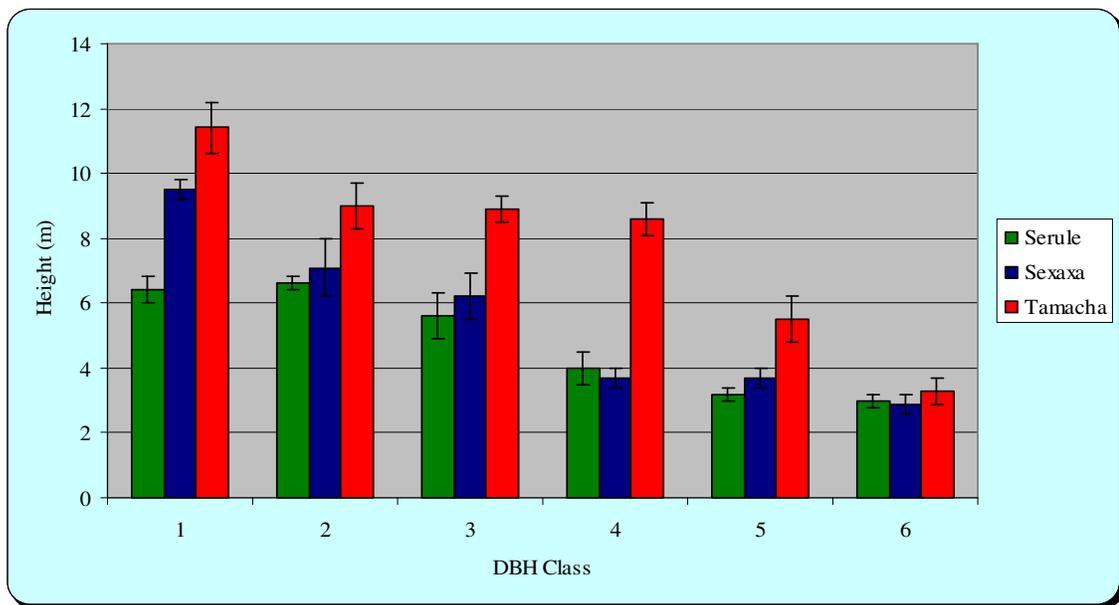
Figure 4.2: Mean tree height per *DBH* class

The mean tree height per site was also found to be higher at Tamacha (7.8 ± 0.5 m) followed by Sexaxa (5.5 ± 0.5 m) and lastly Serule (4.8 ± 0.3 m) (Figure 4.3).
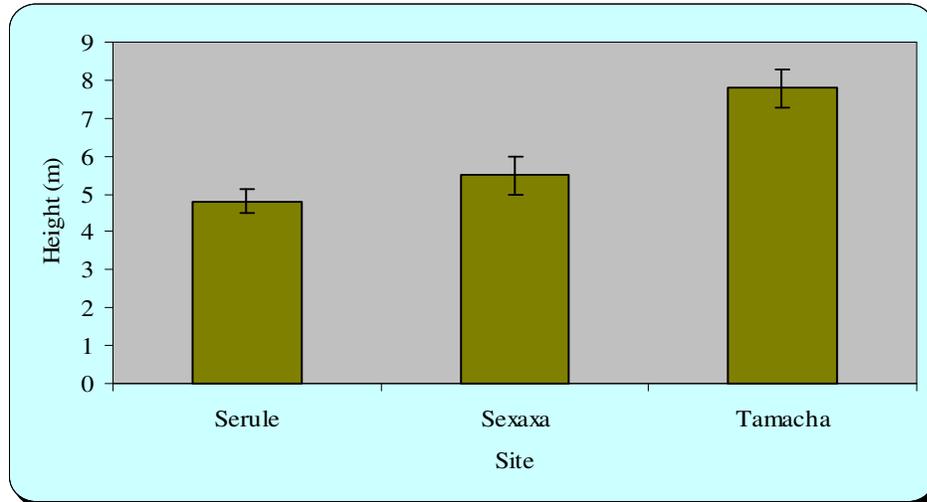
Figure 4.3: Mean tree height per site

While there were no significant differences ($p > 0.05$) between the mean tree heights for the Sexaxa and Tamacha sites, the mean tree height for Serule was significantly different ($p < 0.05$) from the other two (2) sites. The significant differences between the Serule site and the other two (2) sites of Sexaxa and Tamacha may be attributed to the variations in the growth architecture of the mopane trees at the three (3) sites. The mopane trees at the hotter and wetter Sexaxa and Tamacha sites mainly occur as large and tall trees (cathedral mopane), while the mopane at the drier and cooler Serule site are shorter and shrubby, and have more branches when compared with the other two study sites.

The high temperatures and amount of rainfall (Figures 3.1, 3.2 and 3.3) received by Sexaxa and Tamacha may be influential on the growth architecture of the mopane trees in those areas because the findings showed that generally tree height increased with increased rainfall and temperature while branch biomass decreased with increased rainfall and temperature. This is confirmed by Hofstad (2005) who asserted that vegetation in sub-Saharan Africa is determined by temperature and soil moisture availability with the vegetation under intermediate conditions such as Sexaxa and Tamacha dominated by semi-deciduous open forests and woodlands while the drier and hotter conditions such as those in Serule led to other vegetation types such as shrub or

bush land. However, the presence of land-use forms like grazing, benefit the woody component by reducing competing grasses, resulting in relatively high tree growth.

4.1.3 Mean tree biomass

The mean tree fresh biomass per *DBH* class was found to be greatest at Tamacha (Figure 4.4). Sexaxa and Tamacha had the greatest biomass in *DBH* classes 1 and 5 respectively. Serule may have had the greatest biomass in *DBH* class 5 because the mopane in the smaller *DBH* classes at Serule mainly occurs as multi-stemmed shrubs with an increased number of stems per plant, hence the increased tree biomass per plant. At Sexaxa, the large mopane trees in *DBH* class 1 are also multi-stemmed, and this increased the biomass per tree considerably. The multiple stems that are characteristic of this type of woodland cause difficulties for statistical analysis. The individual stems could have been analysed separately, but in such an analysis each observation was not genetically independent from the next, thus violating one of the assumptions for ANOVA and linear regression (Snedecor and Cochran, 1967). Therefore, all of the *DBH*s and total tree heights of the stems per stool were combined and treated as one (1) record for use in the biomass prediction models (Grundy, 1995).

The mean tree fresh biomass per site was greatest at Sexaxa (207.6 ± 46.2 kg) followed by Tamacha (194.5 ± 36.2 kg) and Serule (150.7 ± 25.9 kg) (Figure 4.5). These differences in the mean tree fresh biomass were not significantly different (($p > 0.05$).
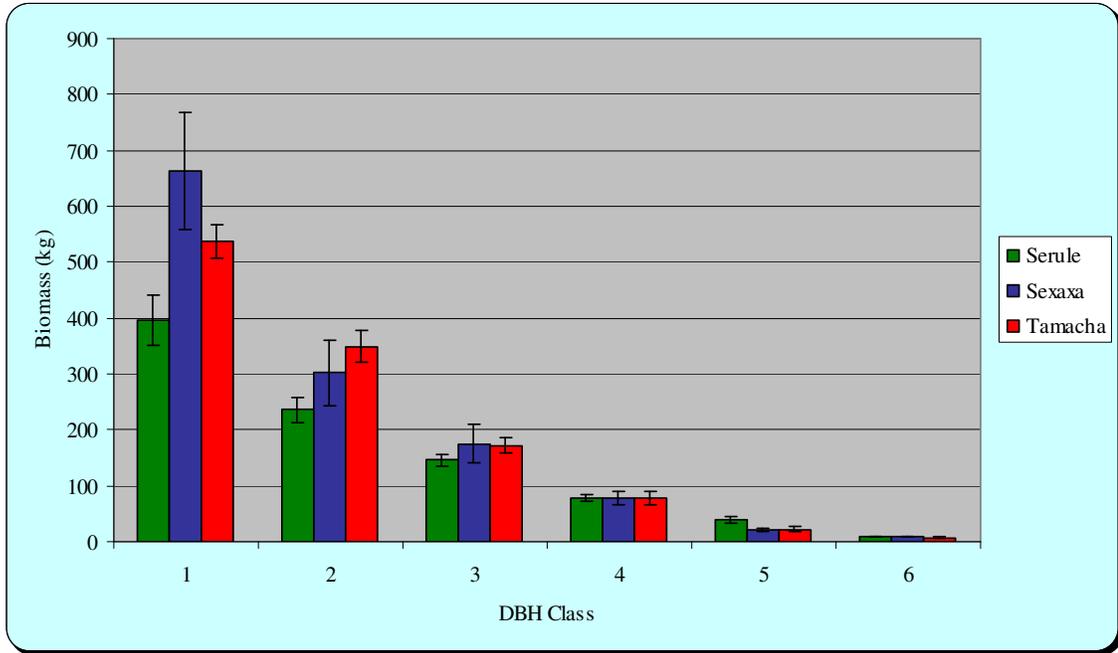
Figure 4.4: Mean tree biomass per *DBH* class
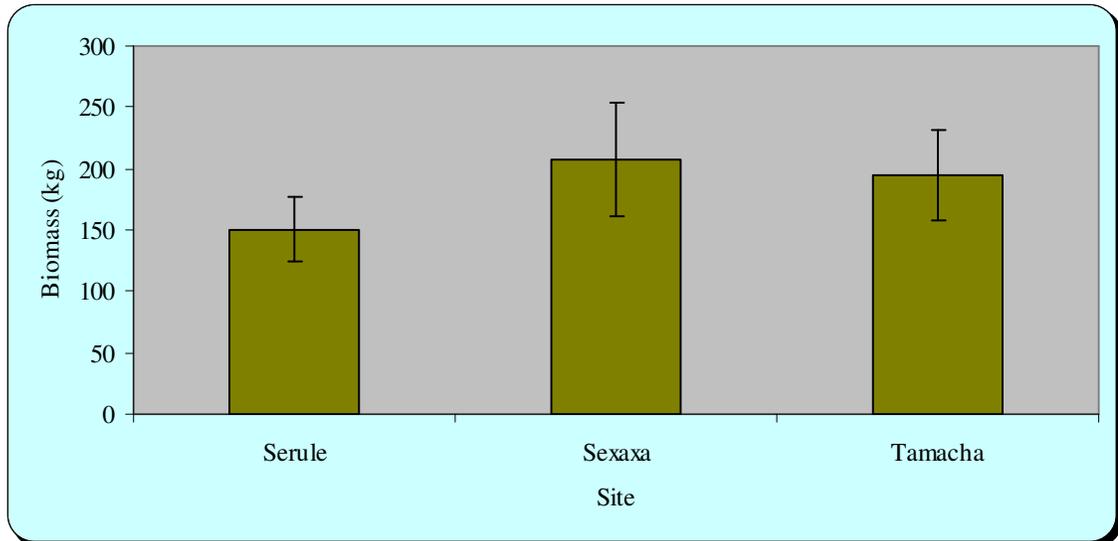
Figure 4.5: Mean tree biomass per site

Generally, it was expected that the mopane trees at Sexaxa and Tamacha which have the highest rainfall, would have the greatest total tree biomass because wetter ecosystems tend to produce larger trees, hence greater biomass (Hofstad, 2005). This is confirmed by the findings of Kemoreile *et al.* (2004) who found out that the average stem biomass

in Tamacha which has comparably higher rainfall was 5 000 kg/ha while it was lower in the drier Serule site which had 3 200 kg/ha. The trees in Tamacha were also found to have fewer branches (500 kg/ha) than in Serule (2 500 kg/ha) (Kemoreile *et al*., 2004). A similar trend was found to be true for *Acacia* woodlands in Botswana where the standing fresh woody biomass was 23 ± 13 tons/ha in Maun compared to Tsabong which had 14 ± 7 tons/ha (Sekhwela, 2002). Tsabong is the driest with an annual rainfall of 250-300 mm while Maun has 450-500 mm per annum.

4.1.4   Mean biomass allocation

The mean biomass allocation per tree is shown per site in Figure 4.6. The stem biomass allocation which was found to be greater at Tamacha (60 ± 22.6%), followed by Serule (53 ± 13.4%) and Sexaxa (48 ± 21%) was not significantly different ($p > 0.05$).
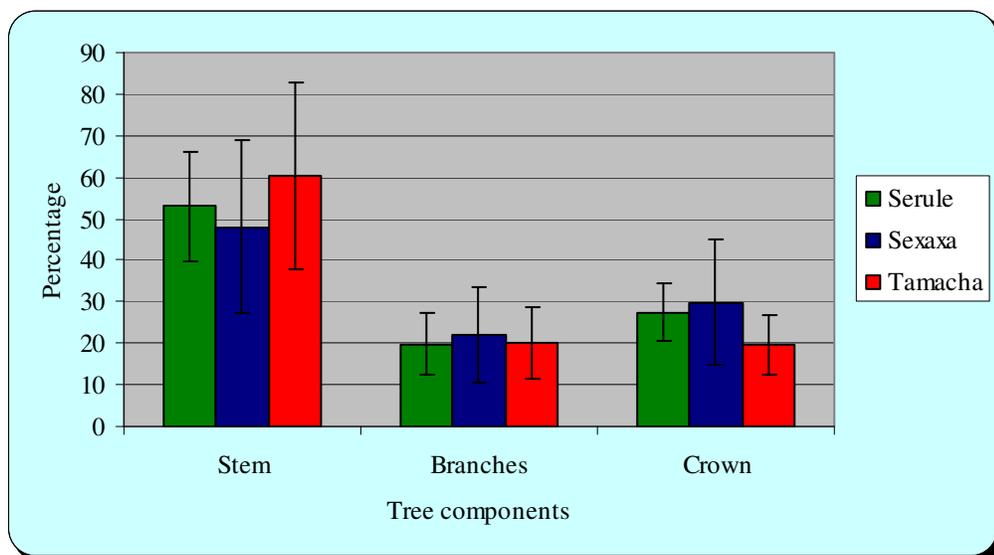
Figure 4.6: Mean tree biomass allocation per site

The mean for the primary branches was greater at Sexaxa (22 ± 11.3%) followed by Tamacha (20 ± 8.5%) and Serule (20 ± 7.3%). The differences in the biomass allocation for the primary branches were also not significantly different ($p > 0.05$). The mean allocation for the crown (including secondary branches) per tree was found to be greater at Sexaxa (30 ± 15.2%), while Serule and Tamacha had 27 ± 6.9% and 20 ± 7.2%

respectively. A one-way ANOVA revealed no significant differences ($p > 0.05$) in the crown biomass allocation.

The results show that the stem biomass was higher than the other biomass components (branches and crown) at all the three sites. The mean biomass allocation for the three sites which was significantly different ($p < 0.05$) was 53.7 ± 1.1% for the stem, 26 ± 1.0% for the crown (including secondary branches) and 21 ± 0.2% for the primary branches (Figure 4.7).
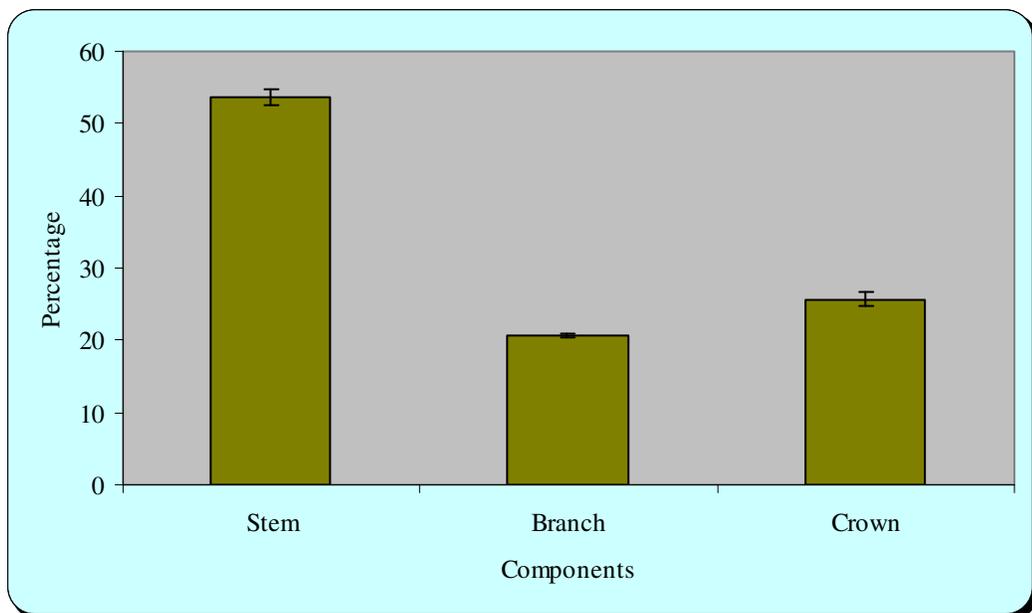
Figure 4.7: Mean tree biomass allocation for the study sites

There were significant differences ($p < 0.05$) between the mean tree biomass allocation for the three sites. The significant differences appear to suggest that the different tree components reflect growth forms exhibited by the trees at the different sites. This is particularly due to the growth architecture of the mopane trees in the study sites (predominantly at Sexaxa and Tamacha) that have large and tall stems that subsequently constitute the bulk of the tree biomass.

The findings are consistent with those by Fuwape *et al*. (2001) on *Gmelina arborea* and *Nauclea diderrichii* in Nigeria, and those by Fuwape and Akindele (1997) on 7-year old *Gmelina arborea* and *Leucaena leucocephala* also in Nigeria. This biomass allocation is also consistent with other species such as *Acacia luederitzii* and *A. mellifera* which produced more stem than branch components in the higher rainfall areas in Botswana (Sekhwela, Yates and Lamb, 2000). In another study (Sekhwela, 2000) it was found that the mopane at Serule had a greater amount of stem (38%) followed by secondary branches (32%) and primary branches (30%). The results from the same study also showed that the mopane trees also had the greatest amount of stem and large branches when compared with *Acacia erubescens* and *Combretum apiculatum*.

While the stem allocation is consistently greater than the branch and crown biomass allocation at all the three sites, the mopane at Sexaxa tends to have more branch and crown biomass than the other two sites with Tamacha having the least amount of crown biomass. This distribution sequence is similar to that for *B. spiciformis* in Mozambique where the nature of the branching architecture of the *B. spiciformis* could be the reason for more branch than stem component (Sitoe *et al*., 2001).

One of the consequences is that communities in different rainfall areas will have different availability of products. The higher rainfall areas will yield more timber from the stem while the low rainfall areas will yield more of poles and browse from the branches and crown respectively. This may form the basis of selective harvesting of various wood products which has been observed in southern Africa (Grundy *et al*., 1993).

Dead and dry fuelwood loads carried on heads of children and women have been found to be composed mainly of branches while fuelwood traders sell logs (large branches and pole size wood). Therefore, the availability of wood which can be harvested and distributed by traders could be assessed in terms of pole and large branch components, while that available for collection by both women and children on head loads could be assessed in terms of small and large branch wood.

The differences in the yield of different wood components are important in the consideration of the kind of management possible and desirable products in view of the needs of a given community, type of woodland, existing land use, and environmental and climatic factors. However, the interaction between climatic and environmental factors affecting the growth and subsequent production levels of trees need comprehensive understanding in order to develop suitable management systems.

4.1.5 Moisture content of components

Figure 4.8 shows that after the drying process, it was found that the crown component had the largest proportion of moisture across all *DBH* classes of the three sites.
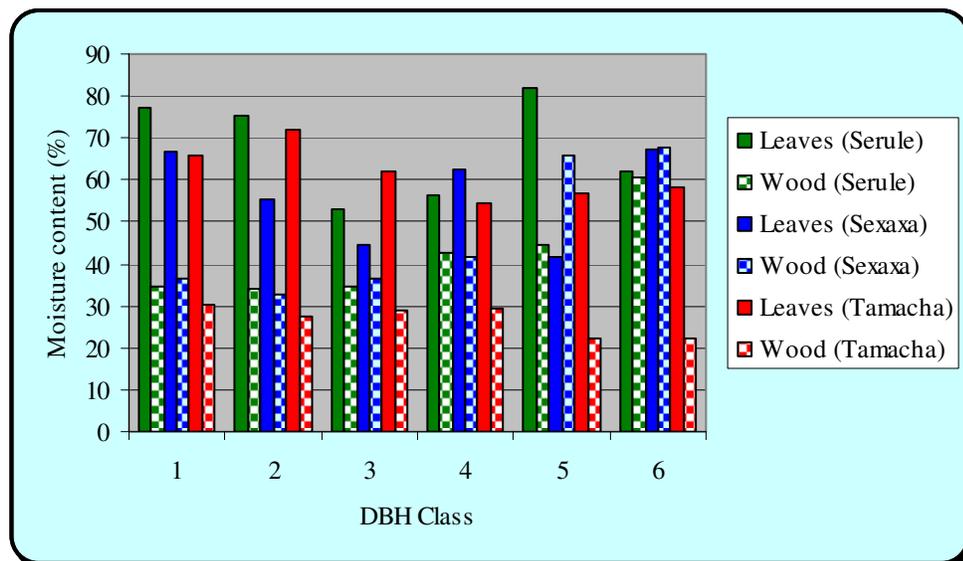
Figure 4.8: Total moisture content of leaves and wood

The exceptions in this study were *DBH* classes 5 and 6 at Sexaxa. The large proportion of water content in the leaves is justified by the result of the high concentration of live cells, which tend to accumulate not only water but also nutrients as a function of transpiration and photosynthesis. These results are similar to those found in another study by Sitoe *et al.* (2001) on *Brachystegia spiciformis* in Mozambique.

The mean moisture content percentage for the wood was 41.9 ± 4.2, 46.9 ± 6.5 and 26.8 ± 1.4 for Serule, Sexaxa and Tamacha respectively, while the mean leaf moisture

content percentage for Serule, Sexaxa and Tamacha was 67.6 ± 4.9, 56.4 ± 4.6 and 61.6 ± 2.6 respectively (Figure 4.9). A one-way analysis of variance (ANOVA) revealed significant differences ($p < 0.05$) in the means of the wood moisture content, while the means of the leaf moisture were not significantly different ($p > 0.05$). However, as shown in Figure 4.8, the moisture content of the leaves and wood across the *DBH* classes per site is highly variable.
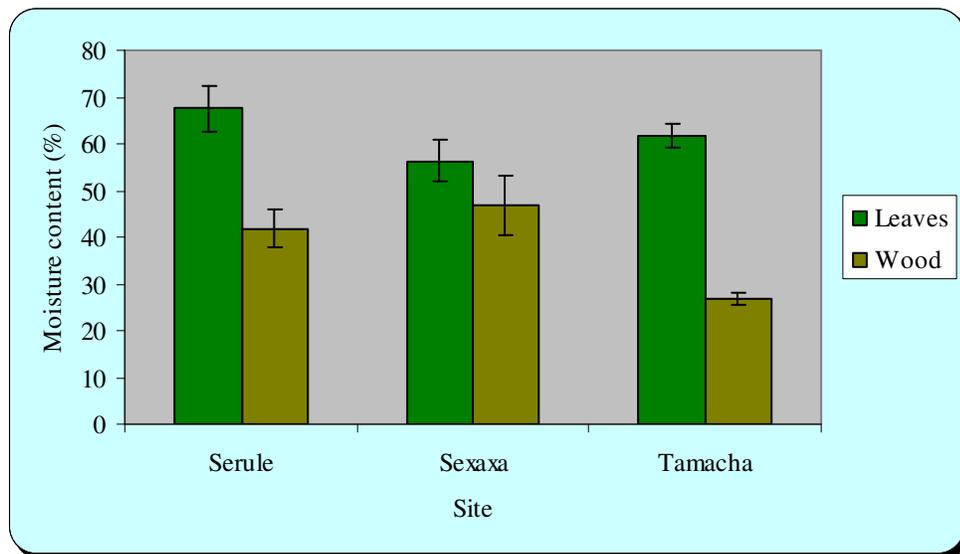
Figure 4.9: Mean leaf and wood moisture content per site

This pattern is similar to that described by Chidumayo (1990) and Grundy (1995) which showed that moisture content was also highly variable in *miombo* woodlands. However, the wood moisture content per site in this study is higher than that of *miombo* woodland given by Grundy (1995) during the same period.

The low moisture content in *DBH* classes 5 and 6 at Sexaxa was probably due to the leaf samples being collected when the day temperature was very high and the leaves had transpired excessively and were already experiencing moisture stress. Alternatively, it could be that the soil was very dry at the time when the leaf samples were collected resulting in little moisture translocation to the leaves.

4.2   Biomass prediction models

The measurements of the stem diameter at 0.15 m; stem diameter at 1.3 m; and stem diameter at 3 m above the ground; tree crown diameter, and total tree height which were transformed to their natural logarithms, were used in the development of biomass models that could be used to predict total tree aboveground biomass also transformed to the natural logarithm. The best fitting regression types at the three study sites were found to be equations of the linear form $y = \beta_0 + \beta_1 x$ (4.1)

and quadratic form $y = \beta_0 + \beta_1 x + \beta_2 x^2$ (4.2)

Where:

y = value of the dependent variable

x = value of the independent variable

β_0 = an estimate of the intercept of the regression line

β_1 and β_2 = estimates of the slope of the regression line

A biomass prediction model for total tree aboveground biomass as a function of both *DBH* and total tree height was not included in this study because the incorporation of tree height in addition to stem diameter as independent variables does not necessarily increase the R^2 value (Chamshama, Mugasha and Zahabu, 2004; Guy, 1981). This is further confirmed by Guy (1981) who found that for a large number of shrubs, stem diameter was the best predictor of aboveground biomass, and that the incorporation of tree height into the equation did not significantly improve the accuracy of the prediction. In Malawi, the inclusion of the logarithm of total height as a second parameter in miombo woodland only improved the R^2 value by 0.5-2% (Abbot *et al.*, 1997).

Furthermore, on practical grounds alone, it is preferable to estimate biomass from stem measurements (particularly *DBH*) because height and crown diameter are often difficult to measure with high accuracy, particularly in closed forests (Abbot *et al.*, 1997; Guy, 1981; Segura and Kanninen, 2005). Furthermore, the use of models where tree biomass is determined from *DBH* only has a practical advantage because most of the inventories

include *DBH* measurements which are easy to carry out accurately in the field (Abbot *et al.*, 1997; Segura and Kanninen, 2005).

4.2.1   Site-specific biomass prediction models for Serule

The results from fitting the site-specific prediction models for the total aboveground biomass of single trees at the Serule site are presented in Table 4.1. The total tree aboveground biomass prediction models that were developed from the measurements of the stem diameter at 0.15 m; stem diameter at 1.3 m; stem diameter at 3 m; and the crown diameter were of the linear form $y = \beta_0 + \beta_1 x$. The total tree aboveground biomass prediction model that was developed from the total tree height was of the quadratic form $y = \beta_0 + \beta_1 x + \beta_2 x^2$.

The *p*-values for the Anderson-Darling normality test on the data were greater than the chosen α-level of 0.05. Thus, the null hypothesis was not rejected. There was not enough evidence to suggest that the data did not follow a normal distribution. The test for the equality of variances was also performed on the data. The *p*-values were greater than the α-level of 0.05. Thus, the null hypothesis was not rejected and the conclusion was that there was no difference between the variances.

Table 4.1: Coefficients and fit statistics from fitting prediction models for the estimation of total tree aboveground biomass in Serule

Dependent variable	Independent variable	Regression coefficients ± standard errors and p-values (in brackets)			R^2 values (%)	p-values for regression model	MSE	Normality test p-values	Equality of variances p-values	n
		b_0	b_1	b_2						
$ln(TTAB)$	$ln(D_{0.15})$	-1.687±0.26 (<0.0001)	2.170±0.90 (<0.0001)		95.4	<0.0001	0.0819	0.123	0.651	30
$ln(TTAB)$	$ln(D_{1.3})$	-0.649±0.17 (<0.0001)	1.963±0.06 (<0.0001)		97.2	<0.0001	0.0499	0.127	0.854	30
$ln(TTAB)$	$ln(D_{3.0})$	1.775±0.15 (<0.0001)	1.351±0.07 (<0.0001)		93.4	<0.0001	0.0949	0.381	0.607	29
$ln(TTAB)$	$ln(CD)$	0.946±0.24 (<0.0001)	2.548±0.17 (<0.0001)		89.2	<0.0001	0.1929	0.512	0.925	30
$ln(TTAB)$	$ln(Ht)$	-5.834±0.26 (<0.0001)	11.360±0.02 (<0.0001)	2.843±0.04 (<0.0001)	73.0	<0.0001	0.4669	0.061	0.552	29

a) *TTAB* is the total tree aboveground biomass   b) $D_{0.15}$ is the stem diameter at 0.15 m   c) $D_{1.3}$ is the stem diameter at 1.3 m
d) $D_{3.0}$ is the stem diameter at 3.0 m   d) *CD* is the crown diameter   e) *Ht* is the total tree height   f) *ln* is the natural logarithm

The strongest relationship that had an R^2 value of 97.2% was for the logarithm of total tree aboveground biomass as a function of the logarithm of stem diameter at 1.3 m while the weakest relationship in Serule, which had an R^2 value of 73%, was for the logarithm of total tree aboveground biomass as a function of the logarithm of total tree height (Table 4.1). The other relationships that were for the logarithm of total tree aboveground biomass as a function of the logarithms of stem diameter at 0.15 m; the stem diameter at 3 m; and the crown diameter had R^2 values of 95.4%, 93.4% and 89.2% respectively.

4.2.1.1 Biomass model for Serule estimated by means of stem diameter at 0.15 m

The plot of the data together with the line of best fit showing the relationship between the logarithm of total tree aboveground biomass estimated by means of the logarithm of stem diameter at 0.15 m are presented in Figure 4.10. The predicted and residual values for the logarithm of the total tree aboveground biomass estimated by means of the logarithm of stem diameter at 0.15 m are shown in Figure 4.11.
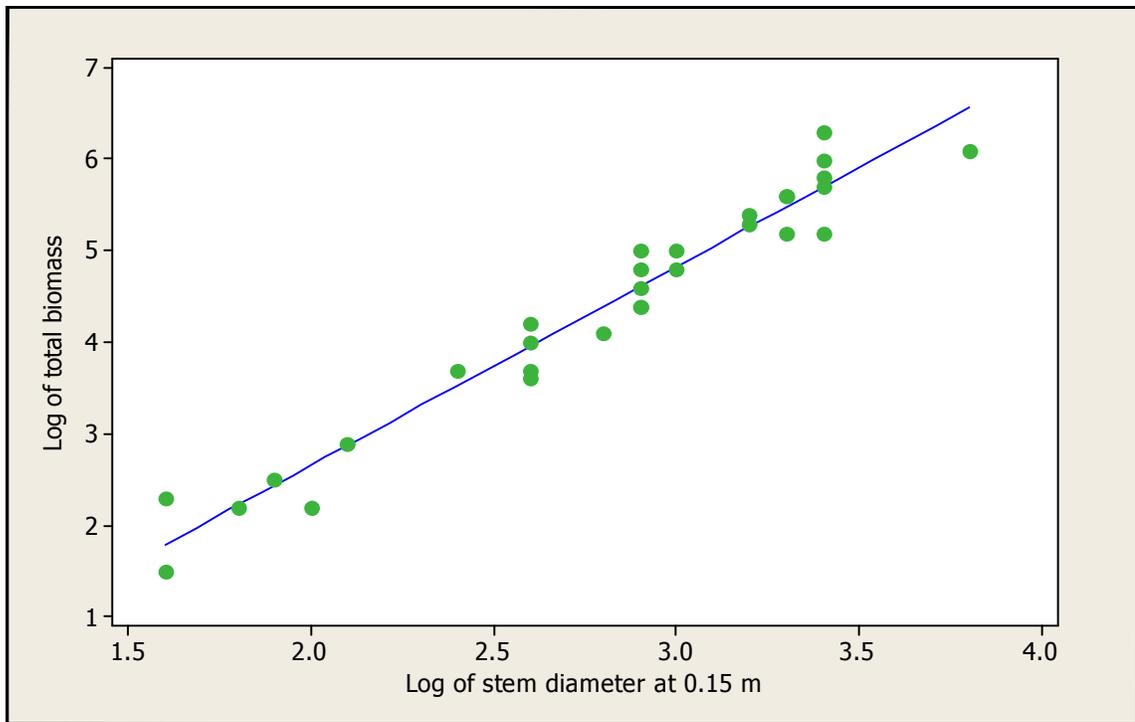
Figure 4.10: The plot and line of best fit for logarithm of total tree aboveground biomass in Serule estimated by logarithm of stem diameter at 0.15 m

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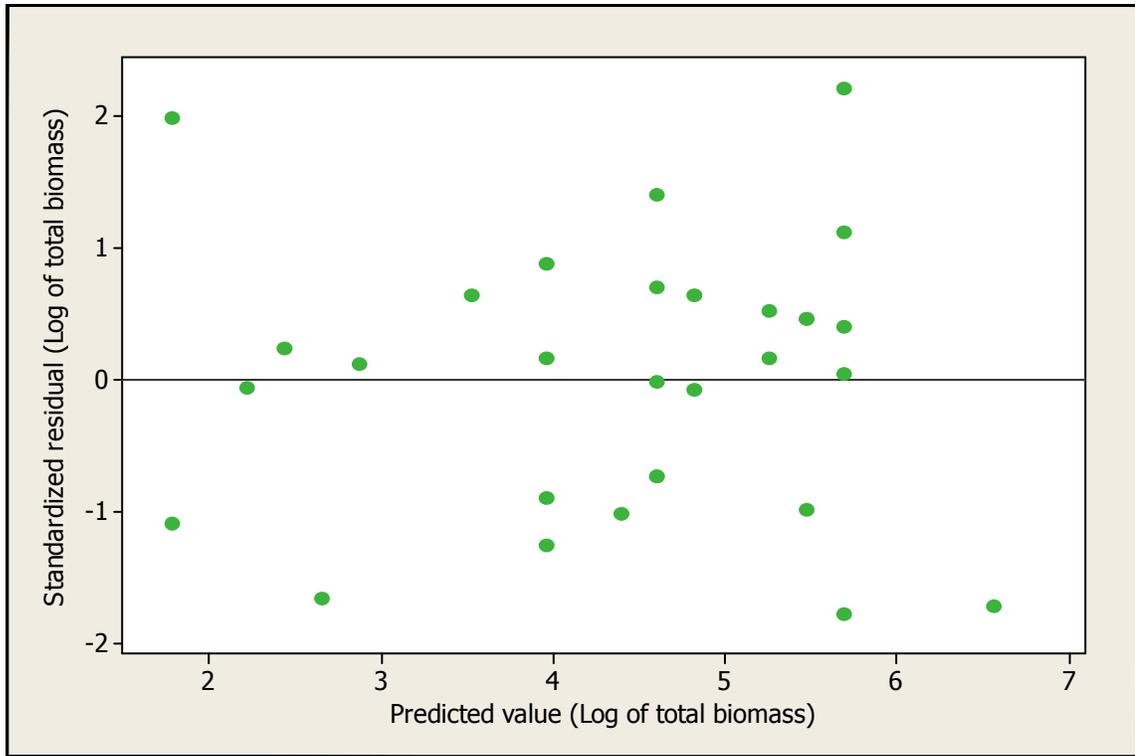
Figure 4.11: Predicted and residual values for logarithm of total tree aboveground biomass in Serule estimated by logarithm of stem diameter at 0.15 m

It is clear from the plot of the data together with the line of best fit in Figure 4.10 that there is a positive linear relationship between the stem diameter at 0.15 m and the total tree aboveground biomass as indicated by the high R^2 value of 95.4%. In spite of the presence of one standardized residual which had an absolute value that is greater than two (2) in the upper right corner of Figure 4.11, the residuals appear to be randomly scattered about the zero line. There is no discernible pattern even for small values in the scatter of the predicted and residual values of the logarithm of total tree aboveground biomass. The random scatter of the residuals suggests that the biomass prediction model provides a good fit to the data. The diagnostic tests that were performed on the data revealed that there were no influential observations in the data set.

The *p*-values indicate whether the coefficients are significantly different from zero, $p <$ α-level indicating significance. Thus, for these data the parameter estimates for the intercept and slope together with the overall fit of the model are significantly different

from zero ($p < 0.0001$) (Table 4.1). The small range of the standard error intervals reflects the narrow variation between the observed and predicted values in Figure 4.10. The error mean square hereby designated as *MSE* is the variance about the regression line. The *MSE* for the data is 0.0819, which suggests that there is little variance in the observations.

4.2.1.2 Biomass model for Serule estimated by means of stem diameter at 1.3 m

The plot of the data together with the line of best fit showing the relationship between the logarithm of total tree aboveground biomass and the logarithm of stem diameter at 1.3 m is presented in Figure 4.12. The fitting of the biomass prediction model estimated by the logarithm of stem diameter at 1.3 m resulted in an R^2 of 97.2%. This implies that only 2.8% of the variability has not been accounted for by the biomass prediction model. The results from fitting the biomass prediction model in Table 4.1, the plot of the data together with the line of best fit in Figure 4.12 and the predicted and residual values in Figure 4.13 indicate that the biomass prediction model provides a good fit to the data.
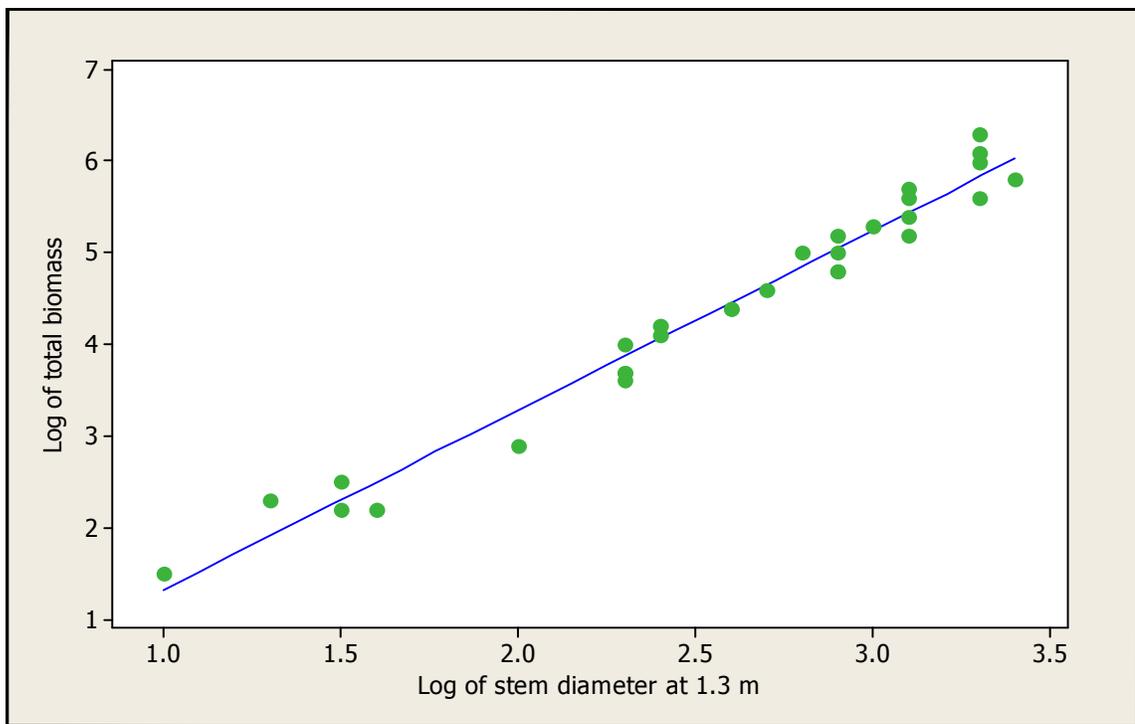
Figure 4.12: The plot and line of best fit for logarithm of total tree aboveground biomass in Serule estimated by logarithm of stem diameter at 1.3 m

The results from fitting the biomass prediction model for the estimation of logarithm of total tree aboveground biomass in Serule using the logarithm of stem diameter at 1.3 m as the independent variable are presented in Table 4.1. The p-values for the intercept and the slope show that the constant (intercept) and the coefficient (slope) are both significantly different from zero ($p < 0.0001$). The overall fit of the biomass prediction model is also significantly different from zero ($p < 0.0001$). The *MSE* of 0.050 further indicates that there is little variance in the observations as indicated by the scatter of the observations around the line of best fit in Figure 4.12.

The predicted and residual values in Figure 4.13 also suggest that the biomass prediction model provides a good fit to the data because they did not exhibit any clear systematic variation and they fluctuate in a random pattern around the zero line.
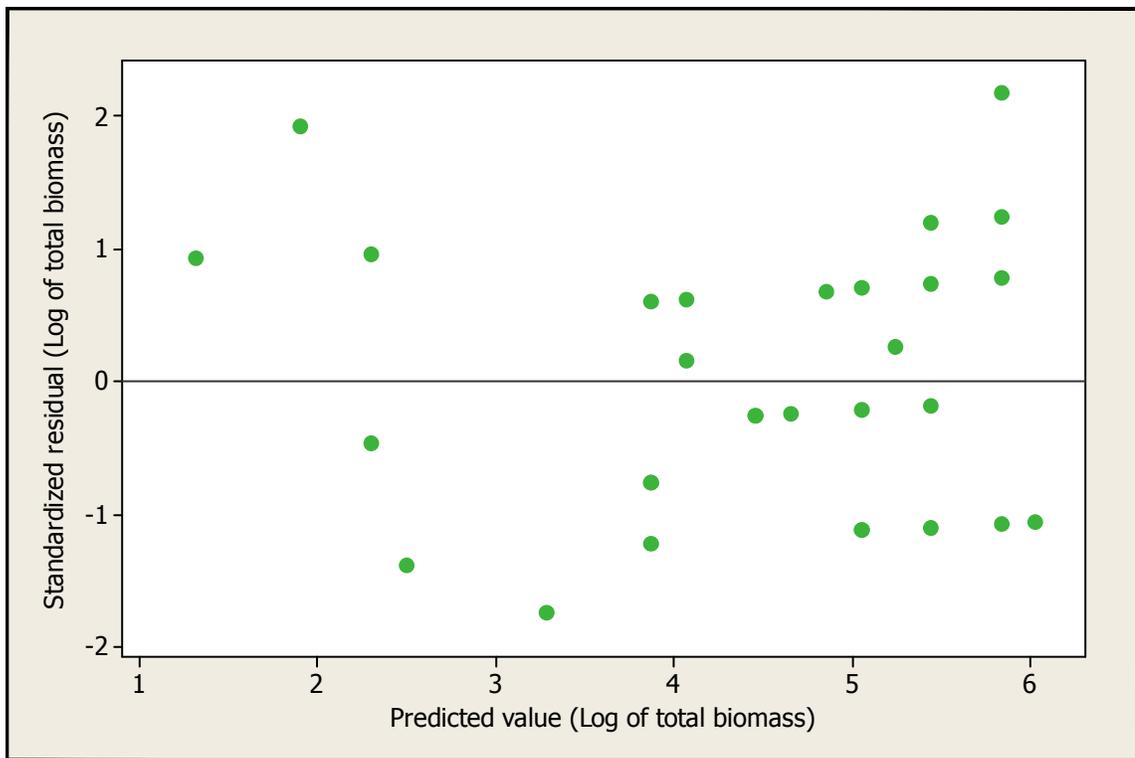

Figure 4.13: Predicted and residual values for logarithm of total tree aboveground biomass in Serule estimated by logarithm of stem diameter at 1.3 m

The plot in Figure 4.13 shows that there is one observation that is an outlier because it has a standardized residual that is greater than two (2). The observation was not too far outside the criterion of ±2.0, and the random scatter of the residuals does not suggest that the variable was influencing the response (total aboveground biomass) in a systematic way. Furthermore, the diagnostic tests performed on the data did not indicate that it was an influential observation. Thus, the exclusion of this point in the data analysis did not seem to be required, more so that the R^2 value of the biomass prediction model was extremely high.

4.2.1.3 Biomass model for Serule estimated by means of stem diameter at 3 m

It is evident from the results of fitting the biomass prediction model in Table 4.1 that the logarithm of total tree aboveground biomass can be adequately predicted by the logarithm of stem diameter at 3 m from the ground. However, it must be noted that one (1) observation was excluded from the data analysis after the diagnostic tests indicated that it was an influential observation. Therefore, the results of fitting the biomass prediction model estimated by the logarithm of stem diameter at 3 m are based on 29 observations.

The R^2 value for the biomass model was 93.4%, which just like the R^2 values for the biomass prediction models based on the logarithms of stem diameter at 0.15 m and the stem diameter at 1.3 m was very high. However, the R^2 values for the stem-based independent variables indicate that the fitting of the biomass prediction model estimated by the logarithm of stem diameter at 1.3 m provides the best fit for the data from the Serule site. The intercept and the slope for the biomass prediction model estimated by the stem diameter at 3 m are significantly different from zero, ($p < 0.0001$). The p-value for the overall fit of the biomass prediction model is also significantly different from zero ($p < 0.0001$).

The plot of the data together with the line of best fit estimated by means of the stem diameter at 3 m indicate that a linear equation provides a good fit to the data because the

observations lie fairly close to the regression line and the points do not appear to present any curvature around the line of best fit (Figure 4.14).

The standardized residuals in Figure 4.15 which shows the plot of the predicted and residual values for the total tree aboveground biomass fluctuate randomly around the zero line and do not show any evidence of curvature. Furthermore, the presence of one standardized residual in the bottom right corner of the plot, which has an absolute value that is less than -2, did not seem to influence the dependent variable (total aboveground biomass) in a systematic way. The diagnostic tests that were performed on the data did not show that it was an influential observation.
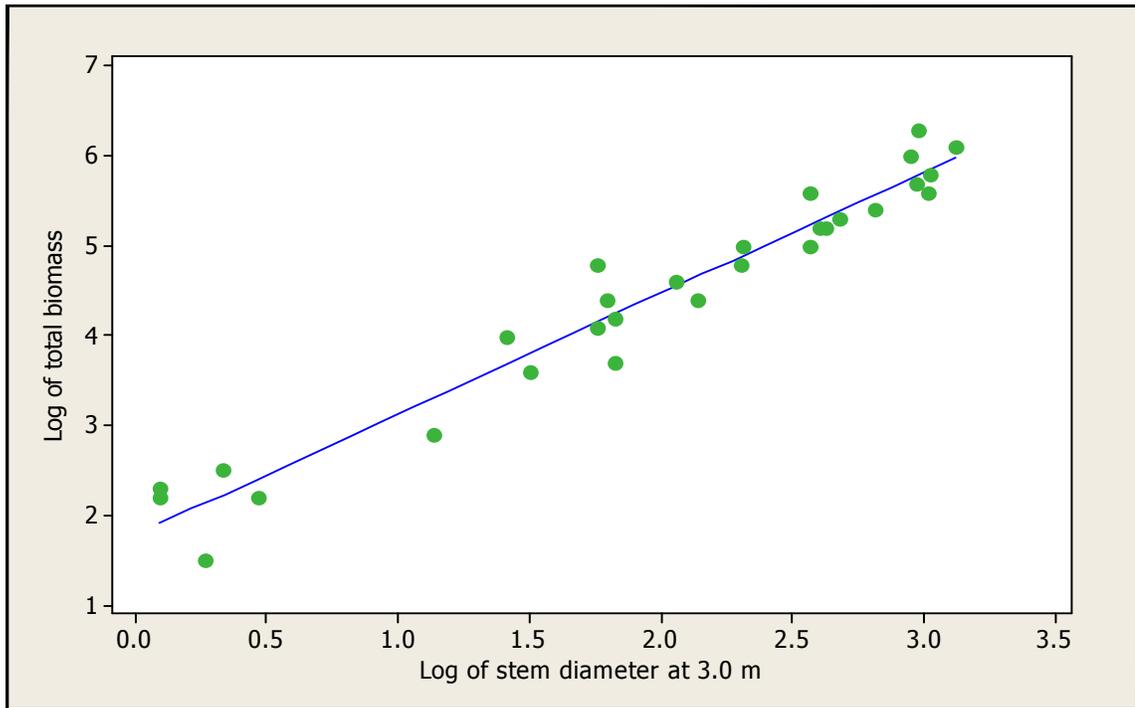

Figure 4.14: The plot and line of best fit for logarithm of total tree aboveground biomass in Serule estimated by logarithm of stem diameter at 3 m
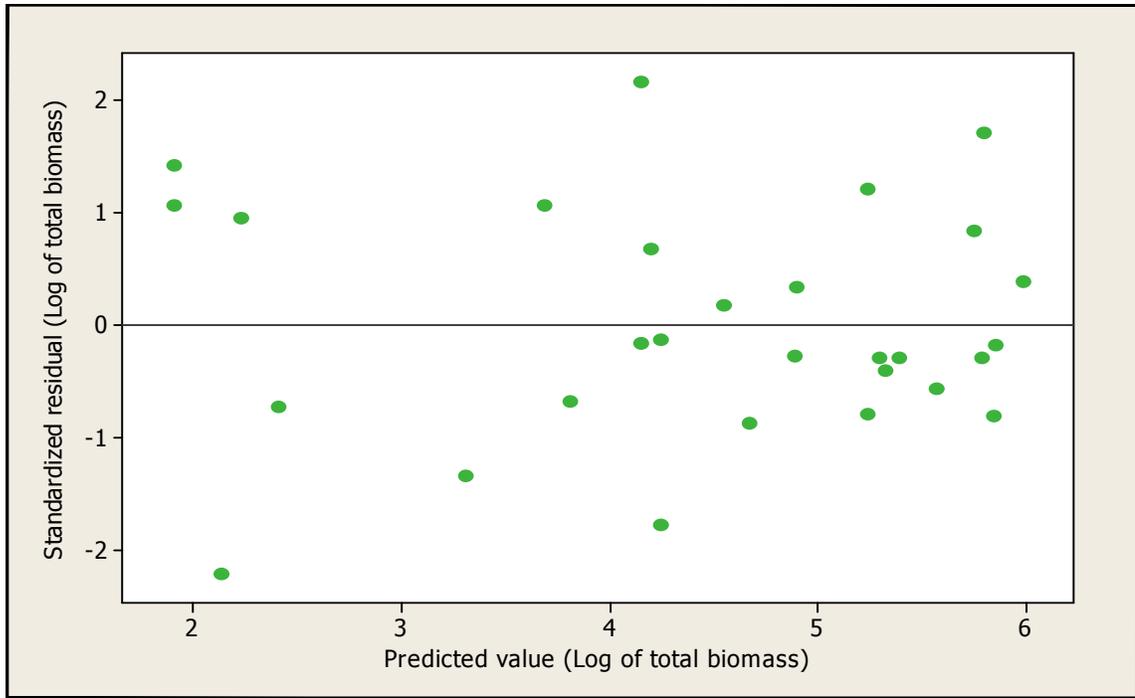
Figure 4.15: Predicted and residual values for logarithm of total tree aboveground biomass in Serule estimated by logarithm of stem diameter at 3 m

4.2.1.4 Biomass model for Serule estimated by means of crown diameter

The logarithm of total tree aboveground biomass can also be accurately predicted by the logarithm of crown diameter as reflected by the high R^2 value of 89.2% in Figure 4.16. Additionally, the plot of the data together with the line of best fit for the regression model indicates that the model provides a good fit to the data and no additional terms are required.

A complementary test of the goodness of fit that involves examining the scatter of the predicted and residual values (Figure 4.17) around the regression line did not indicate that there was any bias in the scatter of the residuals around the regression line. There is no systematic variation in the residuals that suggests that there is an apparent rule for determining whether any particular residual is positive or negative. This indicates that the biomass prediction model provides a good fit to the data.
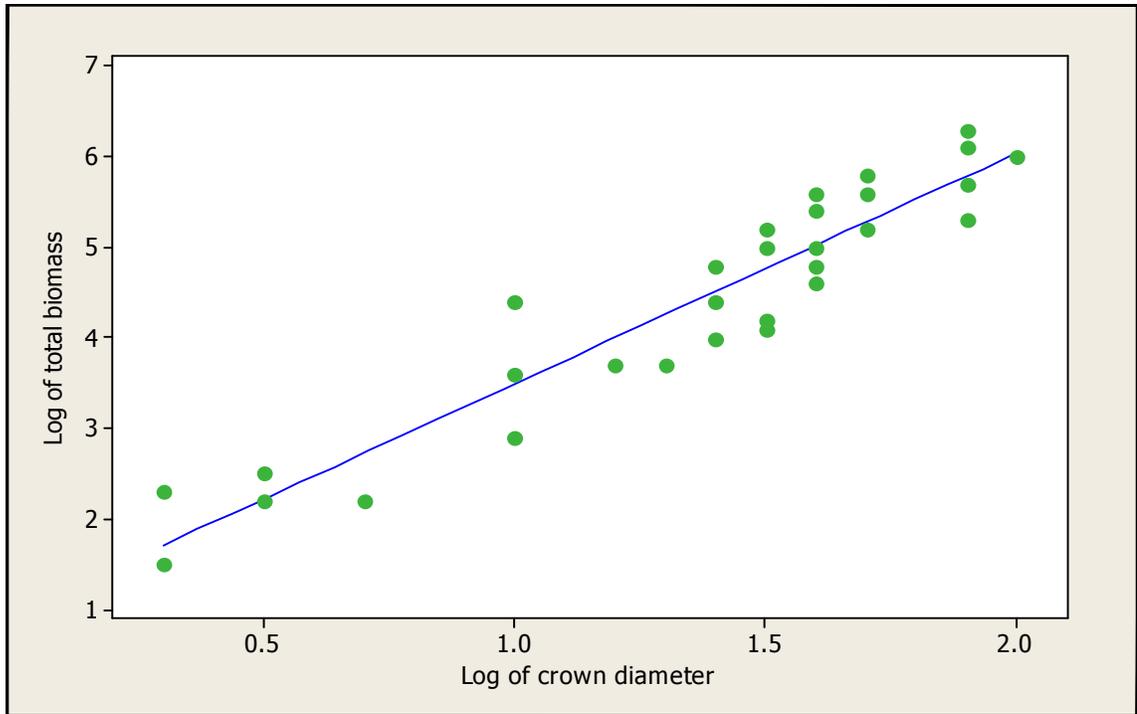
Figure 4.16: The plot and line of best fit for logarithm of total tree aboveground biomass in Serule estimated by logarithm of crown diameter
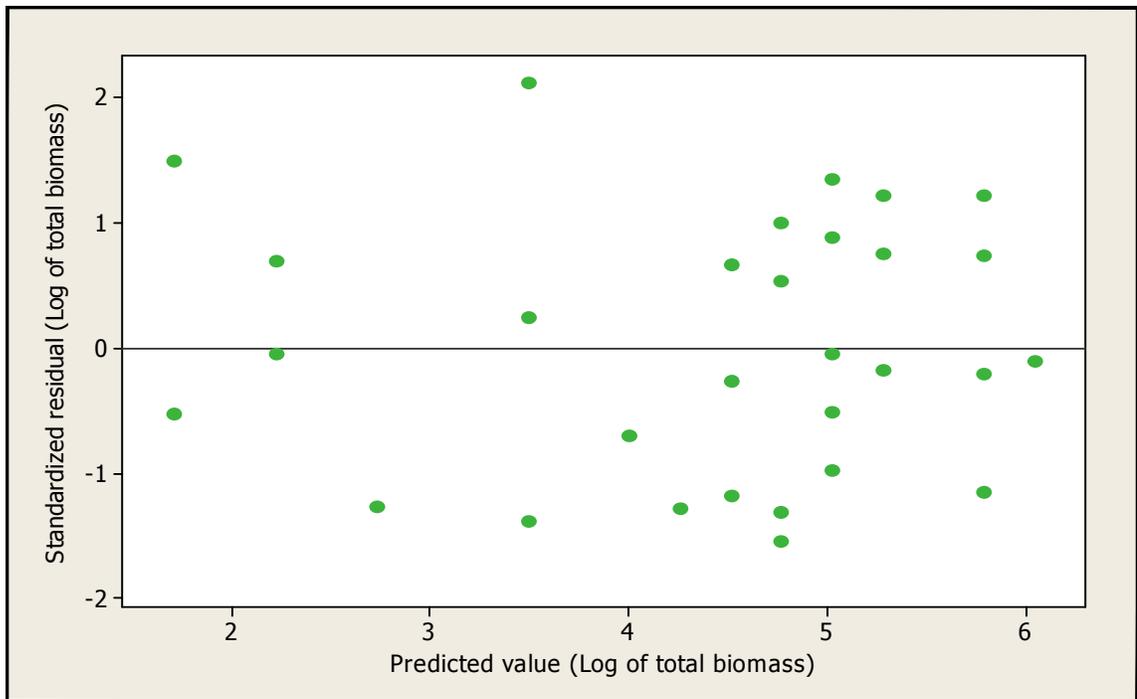

Figure 4.17: Predicted and residual values for logarithm of total tree aboveground biomass in Serule estimated by logarithm of crown diameter

The results from fitting the biomass prediction model estimated by the logarithm of crown diameter are presented in Table 4.1. The p-values for the intercept, the slope and the overall fit of the regression model are significantly different from zero ($p < 0.0001$).

4.2.1.5 Biomass model for Serule estimated by means of total tree height

The plot of the logarithm of total tree aboveground biomass as estimated by the logarithm of total tree height indicates a curvi-linear trend (Figure 4.18). Therefore, a higher-order biomass prediction model whose coefficients are shown in Table 1 was fitted to the data. The higher-order model of a quadratic form was significantly different from zero ($p < 0.0001$) and resulted in an R^2 value of 73%.
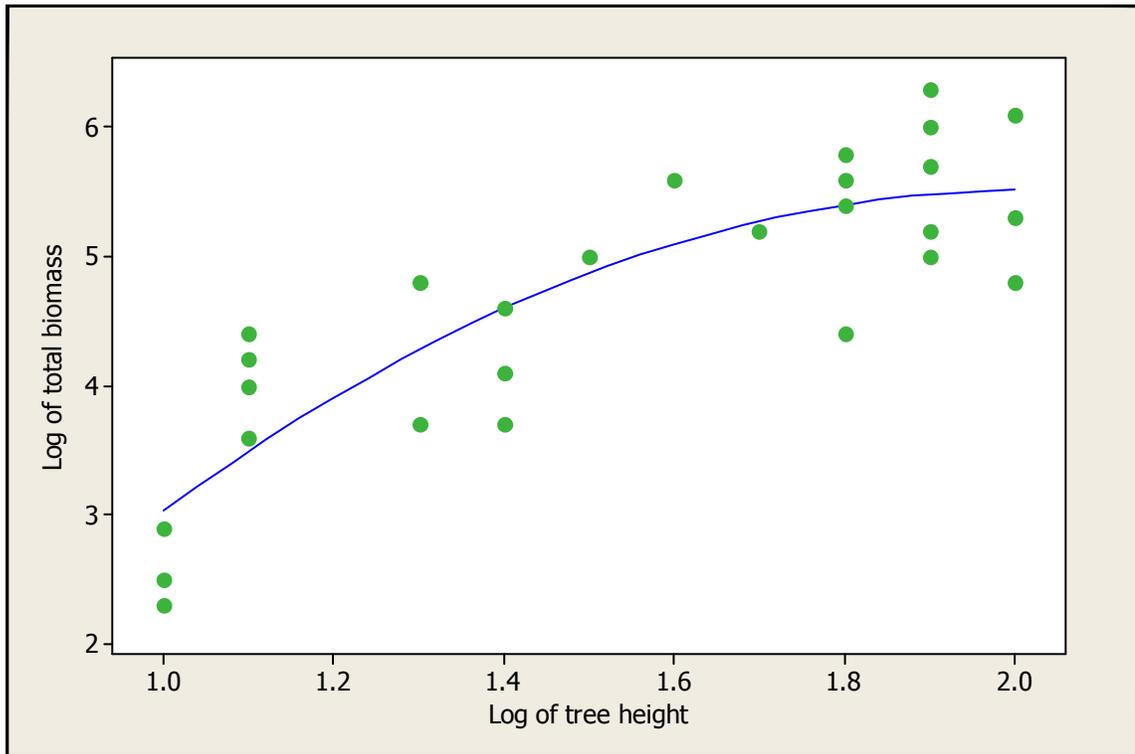
Figure 4.18: The plot and line of best fit for logarithm of total tree aboveground biomass in Serule estimated by logarithm of total tree height

The residuals of the total tree aboveground biomass displayed a slight curvi-linear pattern around the zero line, which suggested that a higher-order term of the independent variable must be included in the biomass prediction model. From left to right, the

residuals increased in value and became positive (above the regression line) before gradually decreasing and becoming negative again. However, the fitting of a higher-order biomass prediction model of the quadratic form resulted in the random scatter of the residuals around the zero line as shown in Figure 4.19. The diagnostic tests that were performed on the data indicated the presence of one influential observation. The observation was excluded from the data analysis.
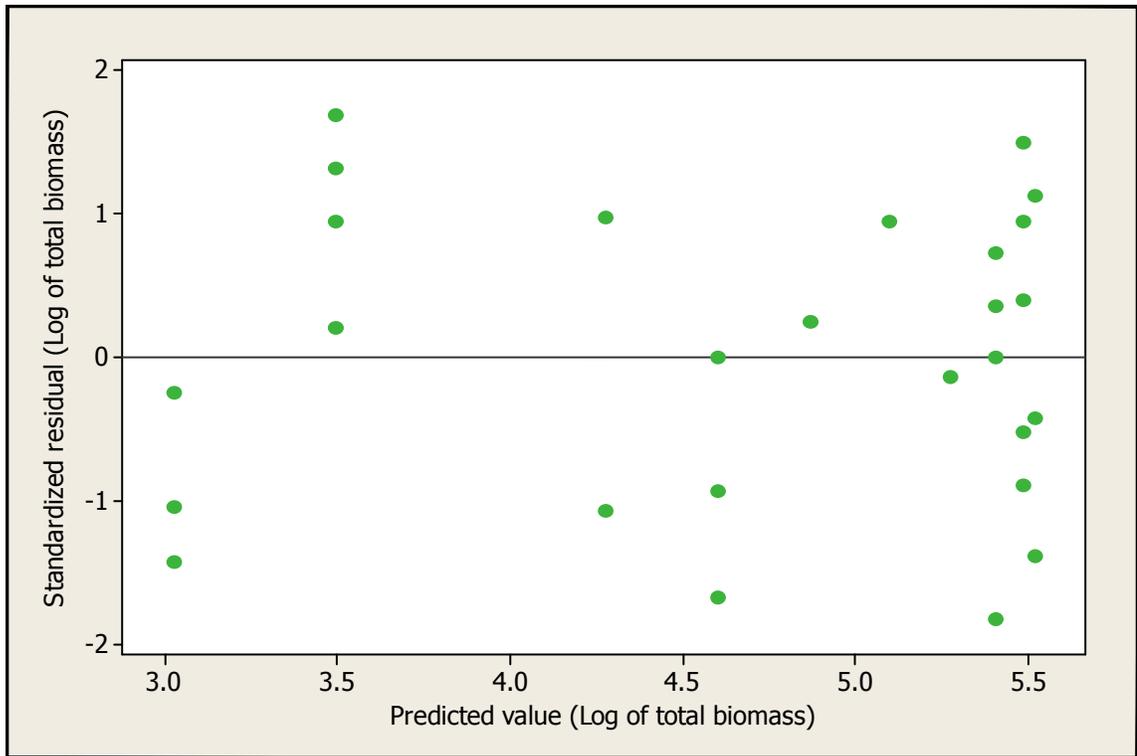
Figure 4.19: Predicted and residual values for logarithm of total tree aboveground biomass in Serule estimated by logarithm of total tree height

The *p*-values of the intercept, slope and the overall fit for the higher-order regression model are all significantly different from zero, ($p < 0.0001$) (Table 4.1). The results indicate that the quadratic biomass prediction model provides a good fit to the data.

4.2.1.6 Comparison of the site-specific biomass prediction models for Serule

The different site-specific regression lines are shown in Figure 4.20. It will be seen from Figure 4.20 that two lines of best fit are shown for each independent variable. For each independent variable, there is the line of best fit for the linear equation and another one for the higher-order equation of the quadratic form.
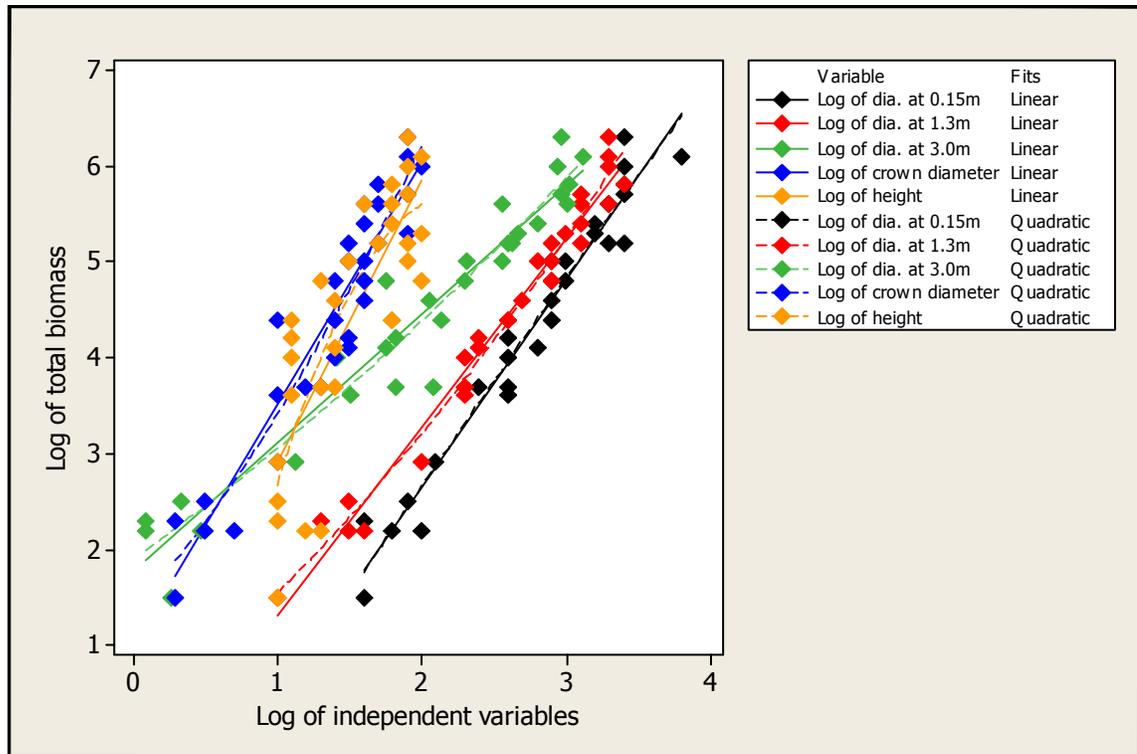
Figure 4.20: Site-specific regression lines for Serule

The two lines have been included for ease of comparison. The plot of the observations and the regression lines show that the biomass prediction models that provide the best fit to the data are of the linear form, with exception of the total tree height where the biomass prediction model of the quadratic form provides the best fit to the data. The biomass prediction model that provides the best fit to the data is the one based on the logarithm of the stem diameter at 1.3 m while the biomass prediction model estimated by the logarithm of the total tree height provides the least-fit to the data. The coefficients and fit statistics from fitting the biomass prediction models are shown in Table 4.1.

4.2.2   Site-specific biomass prediction models for Sexaxa

The coefficients and fit statistics from fitting the site-specific prediction models for the logarithm of total aboveground biomass of individual trees at the Sexaxa site are presented in Table 4.2.   The *p*-values for the Anderson-Darling normality test for normality were greater than the chosen α-level of 0.05.   Thus, the null hypothesis was not rejected.   There was not enough evidence to suggest that the data did not follow a normal distribution.   The Bartlett's test for the equality of variances was also performed on the data.   The *p*-values were greater than the α-level of 0.05.   Thus, the null hypothesis was not rejected and the conclusion was that there was no difference between the variances.

The total tree aboveground biomass prediction models that were developed from the measurements of the logarithms of stem diameter at 1.3 m; stem diameter at 3 m; the crown diameter; and the total tree height were of the linear form $y = \beta_0 + \beta_1 x$. The total tree aboveground biomass prediction model that was developed from the logarithm of stem diameter at 0.15 m was of the quadratic form $y = \beta_0 + \beta_1 x + \beta_2 x^2$. The results are not consistent with the results from the Serule site where the best fitting biomass prediction model based on the logarithm of stem diameter at 0.15 m was of the linear form while the best fitting biomass prediction model estimated from the logarithm of total tree height was of the quadratic form.

Table 4.2: Coefficients and fit statistics from fitting prediction models for the estimation of total tree aboveground biomass in Sexaxa

Dependent variable	Independent variable	Regression coefficients ± standard errors and p-values (in brackets)			R^2 values (%)	p-values for regression model	MSE	Normality test p-values	Equality of variances p-values	n
		b_0	b_1	b_2						
$ln(TTAB)$	$ln(D_{0.15})$	0.515±0.22 (<0.0001)	0.448±0.08 (<0.0001)	0.356±0.10 (<0.001)	98.7	<0.0001	0.0363	0.107	0.704	28
$ln(TTAB)$	$ln(D_{1.3})$	-1.048±0.14 (<0.0001)	2.189±0.05 (<0.0001)		98.4	<0.0001	0.0419	0.100	0.557	30
$ln(TTAB)$	$ln(D_{3.0})$	1.506±0.25 (<0.0001)	1.564±0.12 (<0.0001)		89.3	<0.0001	0.2815	0.057	0.510	29
$ln(TTAB)$	$ln(CD)$	0.505±0.11 (<0.0001)	2.821±0.21 (<0.0001)		97.1	<0.0001	0.0814	0.066	0.359	25
$ln(TTAB)$	$ln(Ht)$	-0.128±0.48 (<0.0001)	2.845±0.29 (<0.0001)		77.9	<0.0001	0.5632	0.075	0.442	30

a) *TTAB* is the total tree aboveground biomass   b) $D_{0.15}$ is the stem diameter at 0.15 m   c) $D_{1.3}$ is the stem diameter at 1.3 m
d) $D_{3.0}$ is the stem diameter at 3.0 m   d) *CD* is the crown diameter   e) *Ht* is the total tree height   f) *ln* is the natural logarithm

4.2.2.1 Biomass model for Sexaxa estimated by means of stem diameter at 0.15 m

The plot for the data together with line of best fit for the relationship between the logarithm of stem diameter at 0.15 m and the logarithm of total tree aboveground biomass at Sexaxa are shown in Figure 4.20. The plot for the data indicated a curvi-linear trend. Therefore a higher-order model was fitted to the data. The higher-order model was significantly different from zero ($p < 0.0001$). The regression coefficients for the intercept and the slope were also significantly different from zero ($p < 0.0001$) (Table 4.2). The diagnostic tests revealed that there were two (2) influential observations which were subsequently excluded from the data analysis.

The plot of the data together with the fitted line of best fit (Figure 4.21) showed that the higher-order model provided a good fit to the data and it was not justifiable to look further at the more complex models. The *MSE* of 0.0363 further indicated that there was little variance in the observations as indicated by the scatter of the observations around the line of best fit in Figure 4.21. An examination of the scatter of the residuals in Figure 4.22 showed that there is a discernible trend or pattern that suggests that the variances are not constant. There is an increase of the residuals as the predicted values increase. This pattern indicates a problem of heterogeneity of variances. However, the Bartlett's test for the equality of variance revealed that the variance is homogeneous ($p = 0.704$ at an α –level of 0.05) as shown in Table 4.2.
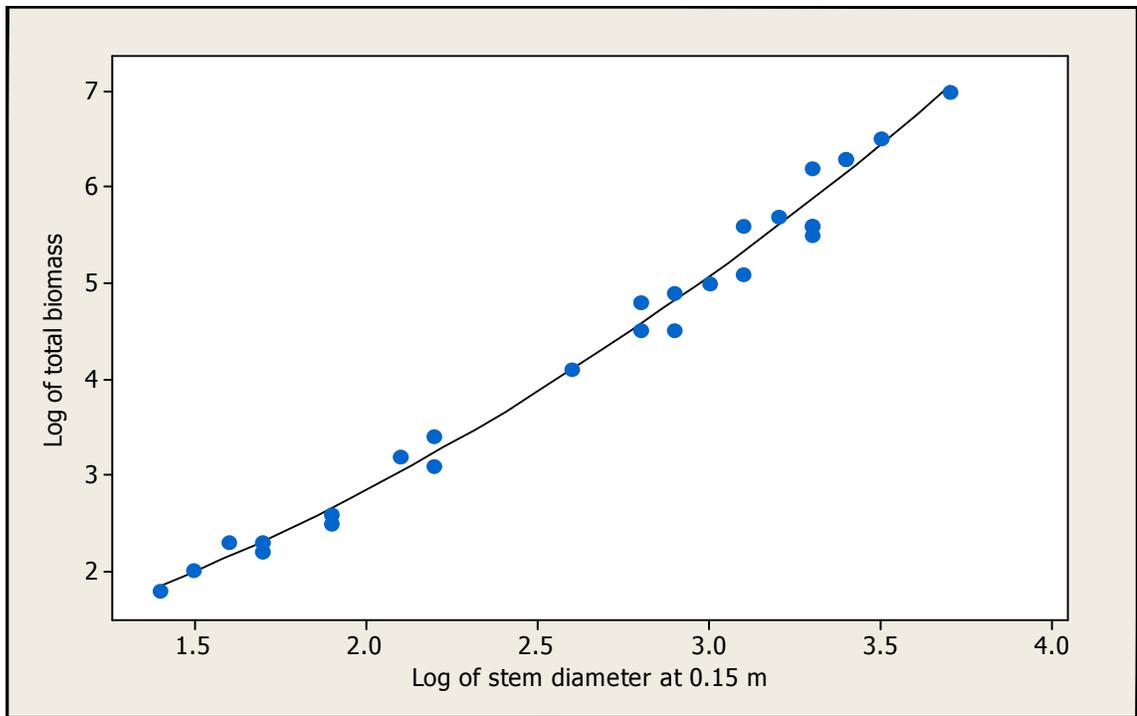
Figure 4.21: The plot and line of best fit for logarithm of total tree aboveground biomass in Sexaxa estimated by logarithm of stem diameter at 0.15 m
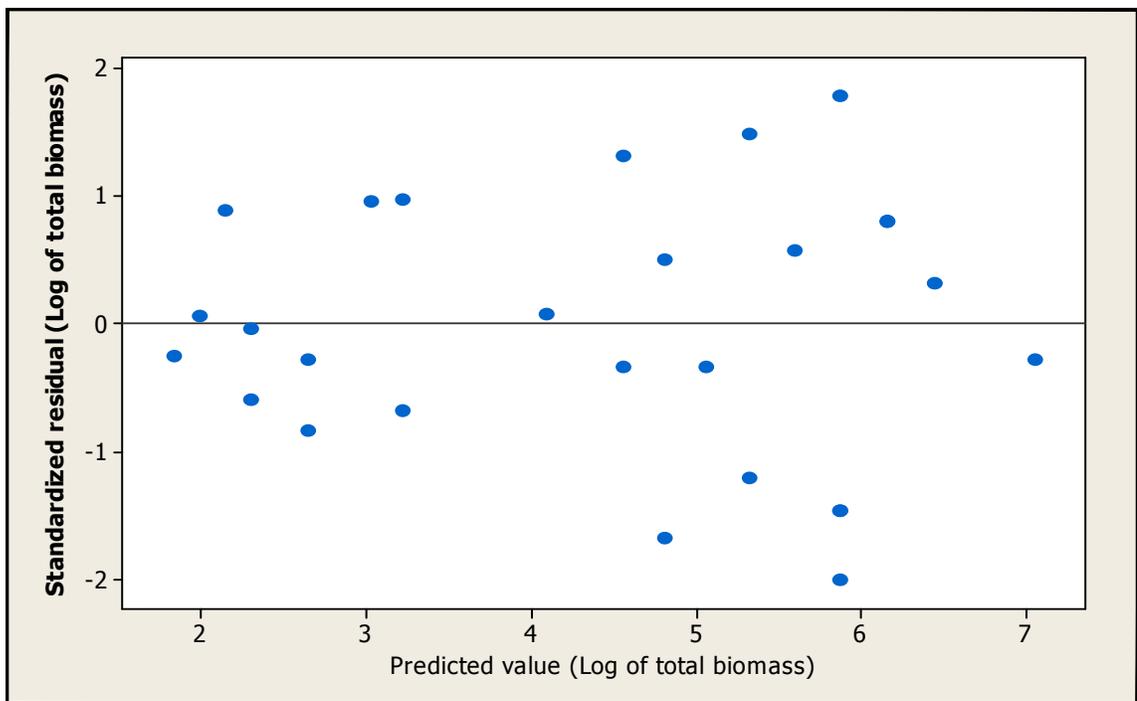

Figure 4.22: Predicted and residual values for logarithm of total tree aboveground biomass in Sexaxa estimated by logarithm of stem diameter at 0.15 m

4.2.2.2 Biomass model for Sexaxa estimated by means of stem diameter at 1.3 m

The plot of the data together with the line of best fit showing the relationship between the logarithm of the total aboveground biomass and the logarithm of the stem diameter at 1.3 m is presented in Figure 4.23. The fitting of the biomass prediction model estimated by the logarithm of stem diameter at 1.3 m resulted in an R^2 of 98.4%. This implies that only 1.6% of the variability has not been accounted for by the biomass prediction model. The high R^2 value (98.4%) for the biomass prediction model is confirmed by the scatter of points around the line of best fit in the plot of the data in Figure 4.23. The points lie fairly close to the line of best fit which suggests that the biomass prediction model provides a good fit to the data.
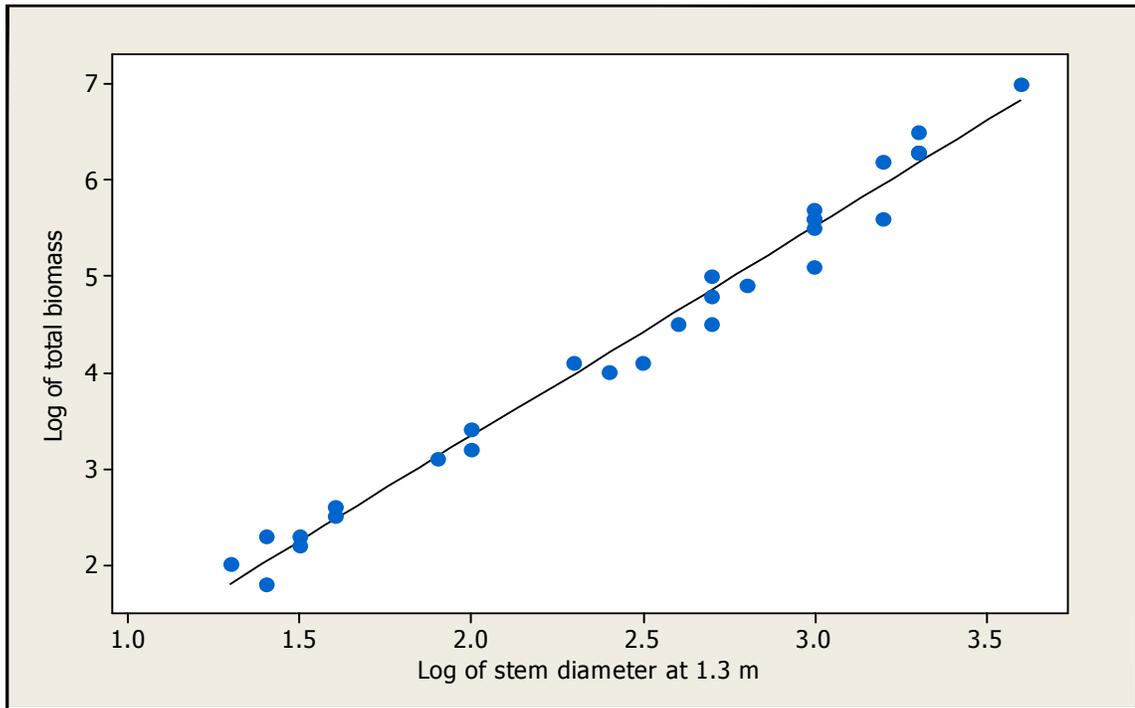
Figure 4.23: The plot and line of best fit for logarithm of total tree aboveground biomass in Sexaxa estimated by logarithm of stem diameter at 1.3 m

The results from fitting the biomass prediction model in Figure 4.23 are presented in Table 4.2. The p-values for the intercept and the slope are both significantly different from zero ($p < 0.0001$). The overall fit of the biomass prediction model is also significantly different from zero ($p < 0.0001$). The *MSE* of 0.0419 further indicates that

there is little variance in the observations as indicated by the scatter of the observations around the line of best fit in Figure 4.23.

The predicted and residual values in Figure 4.24 suggest that the variance of the residuals is not homogeneous. The residuals exhibit a pattern and do not fluctuate in a random pattern around the zero line. The increase of the residuals as the predicted values increase suggests that the variance is heterogeneous. However, the Bartlett's test for the equality of variance that was performed on the data indicated that the variance is homogeneous ($p = 0.0557$) at an α –level of 0.05 (Table 4.2).
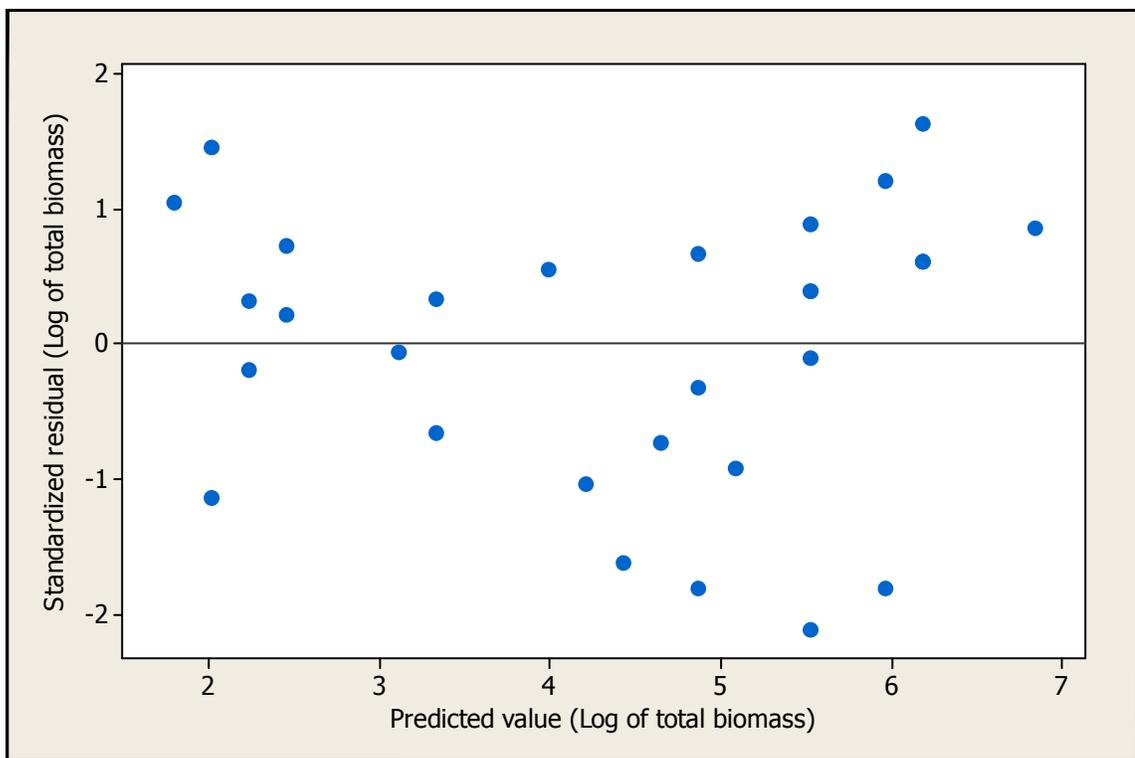
Figure 4.24: Predicted and residual values for logarithm of total tree aboveground biomass in Sexaxa estimated by logarithm of stem diameter at 1.3 m

The plot in Figure 4.24 shows that there is one observation that should be considered as an outlier because of a standardized residual that is greater than two (2). The observation is in the bottom right corner of the plot in Figure 4.24. However, the observation is not too far outside the criterion of ±2.0. The diagnostic tests performed

on the data did not indicate that it was an influential observation. Thus, the exclusion of this point in the data analysis did not seem to be required, more so that the R^2 value of the biomass prediction model was extremely high.

4.2.2.3 Biomass model for Sexaxa estimated by means of stem diameter at 3 m

It is evident from the results of fitting the biomass prediction model in Table 4.2 that the total tree aboveground biomass can be adequately predicted by the stem diameter at 3 m from the ground. However, it must be noted that one observation was excluded from the data analysis after the diagnostic tests indicated that it was an influential observation. Therefore the coefficients and fit statistics of fitting the biomass prediction model estimated by the logarithm of the stem diameter at 3 m are based on 29 observations as shown in Table 4.2.

The R^2 value for the biomass prediction model was 89.3%, which just like the R^2 values for the biomass prediction models based on the stem diameter at 0.15 m and the stem diameter at 1.3 m was very high.   However, the R^2 values for the stem-based independent variables indicate that the fitting of the biomass prediction model estimated by the logarithm of the stem diameter at 0.15 m provides the best fit for the data at the Sexaxa site. The intercept and the slope for the biomass prediction model estimated by the stem diameter at 3 m are significantly different from zero, ($p < 0.0001$). The p-value for the overall fit of the biomass prediction model is also significantly different from zero ($p < 0.0001$).

The plot of the data together with the line of best fit estimated by means of the stem diameter at 3 m (Figure 4.25) indicates that a linear equation provides a good fit to the data because the points lie fairly close to the line of best fit and the observations do not appear to present any curvature around the line of best fit.

The predicted and residual values of the total tree aboveground biomass are shown by the plot in Figure 4.26.
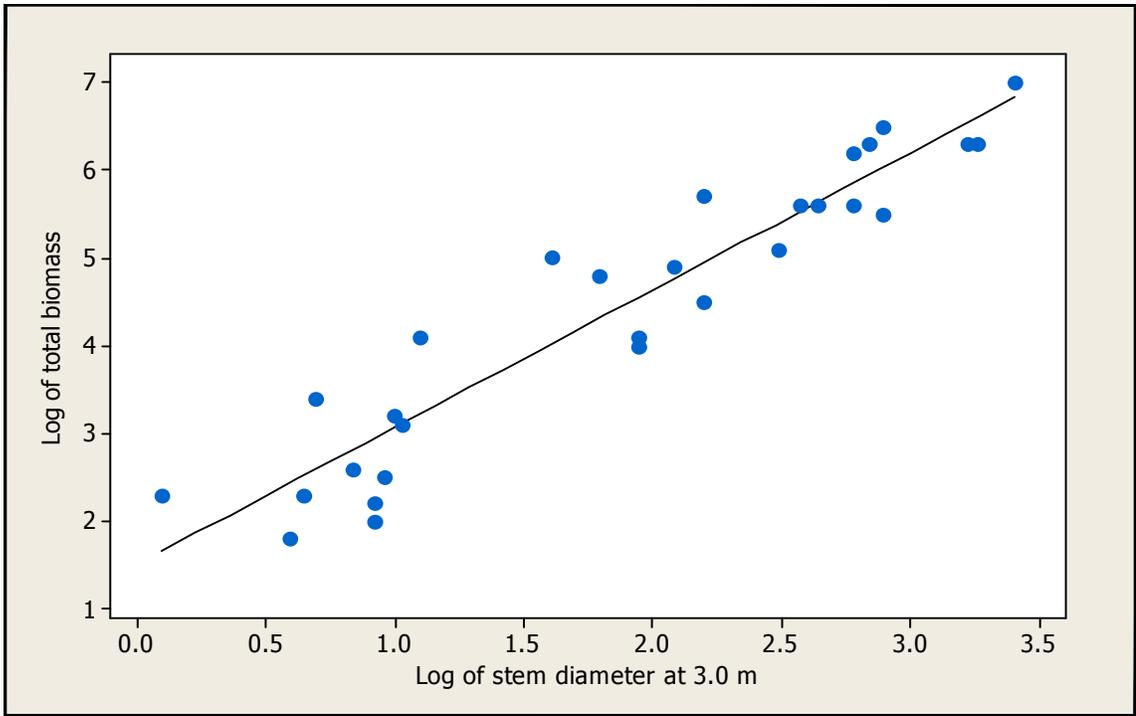
Figure 4.25: The plot and line of best fit for logarithm of total tree aboveground biomass in Sexaxa estimated by logarithm of stem diameter at 3 m
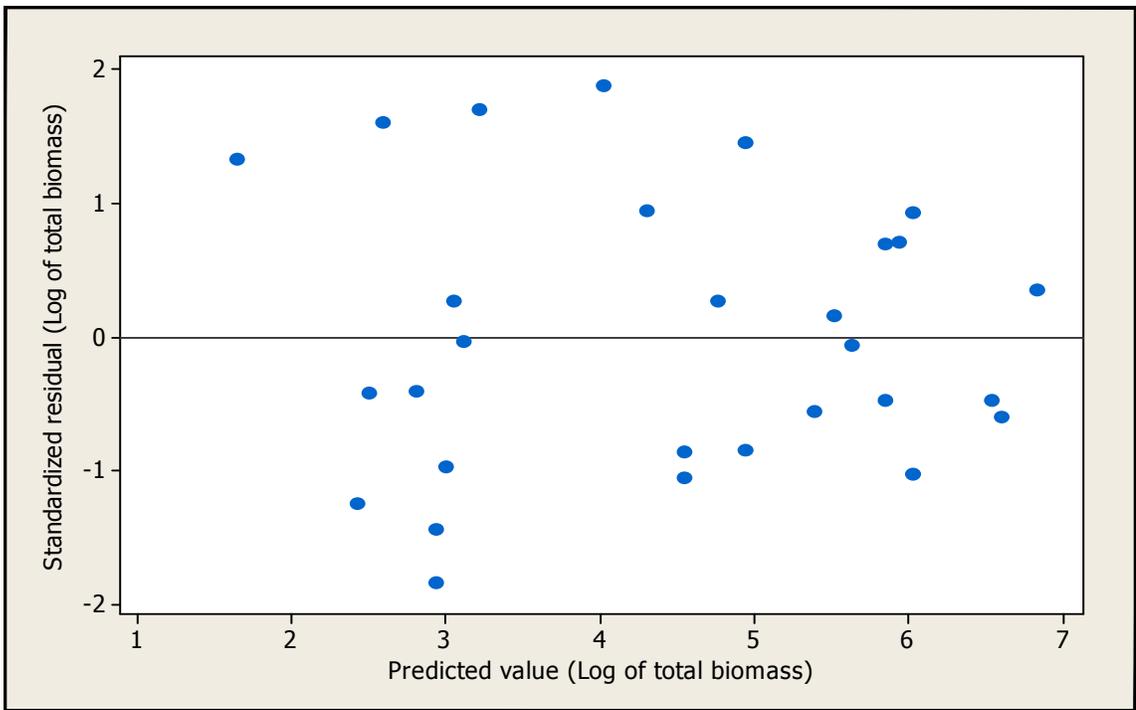

Figure 4.26: Predicted and residual values for logarithm of total tree aboveground biomass in Sexaxa estimated by logarithm of stem diameter at 3 m

Figure 4.26 shows that the variance of the residuals decreases with the predicted values. It will be observed from the plot in Figure 4.26 that as the predicted values increase, there is a narrow scatter of the residuals around the zero line. The residuals decrease with the predicted values in a pattern that looks like a funnel. The fanning or the uneven spread of the residuals across the predicted values indicates inconstant variance. However, the Bartlett's test for the equality of variances revealed that the variances are constant or equal ($p = 0.510$) at an α-level of 0.05 (Table 4.2).

4.2.2.4 Biomass model for Sexaxa estimated by means of crown diameter

It is evident from the results (Table 4.2) of fitting the biomass prediction model that the total tree aboveground biomass can also be adequately predicted by the crown diameter. It must be noted the diagnostic tests indicated that there were five (5) influential observations in the data. This was quite a large number of influential observations for such a small (30 observations) data set. The collection of more data could have probably offset the influence of the five (5) observations. However, without that option, the five (5) influential observations were excluded from the data analysis. The plot of the data and the line of best fit are shown in Figure 4.27 while the predicted and residual values for the total tree aboveground biomass are shown by the plot in Figure 4.28.

The plot of the data together with the line of best fit estimated by means of the logarithm of the crown diameter indicates that the biomass prediction model of a linear form provides a good fit to the data because the points lie fairly close to the line of best fit and the points do not appear to present any curvature around the line of best fit (Figure 4.27). The R^2 value for fitting a biomass prediction model of the linear form to the 25 observations was 97.1%, which just like the R^2 values for the biomass prediction models based on the stem diameter at 0.15 m and the stem diameter at 1.3 m was above 90%.
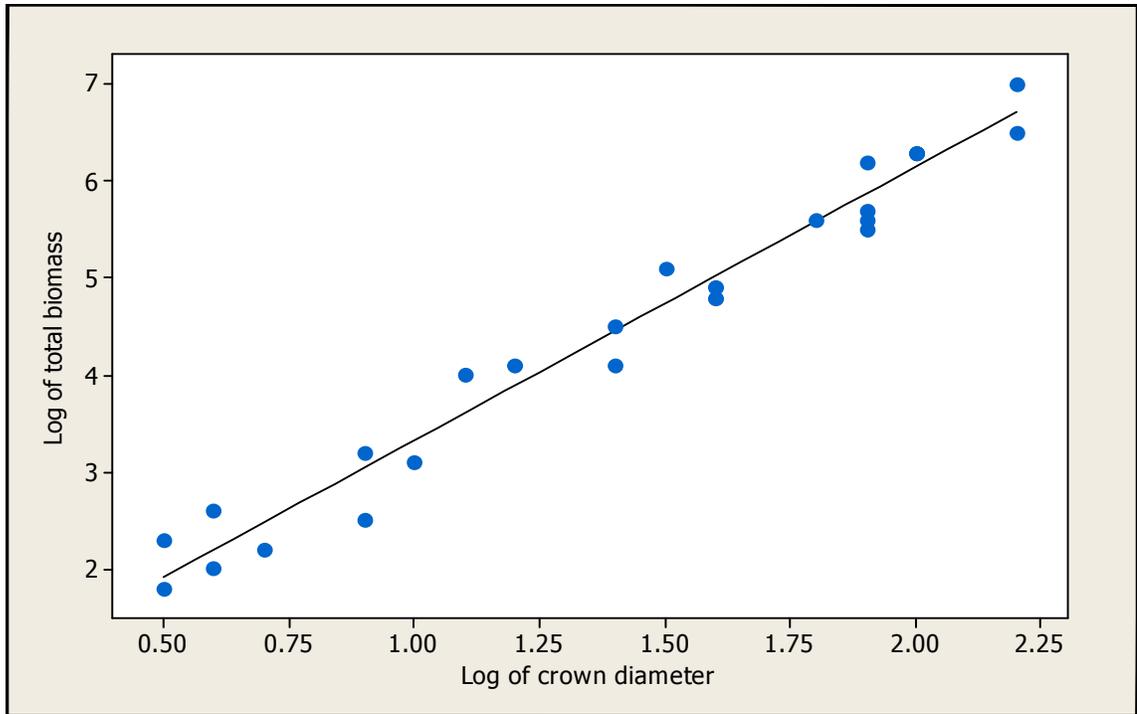
Figure 4.27: The plot and line of best fit for logarithm of total tree aboveground biomass estimated by logarithm of crown diameter
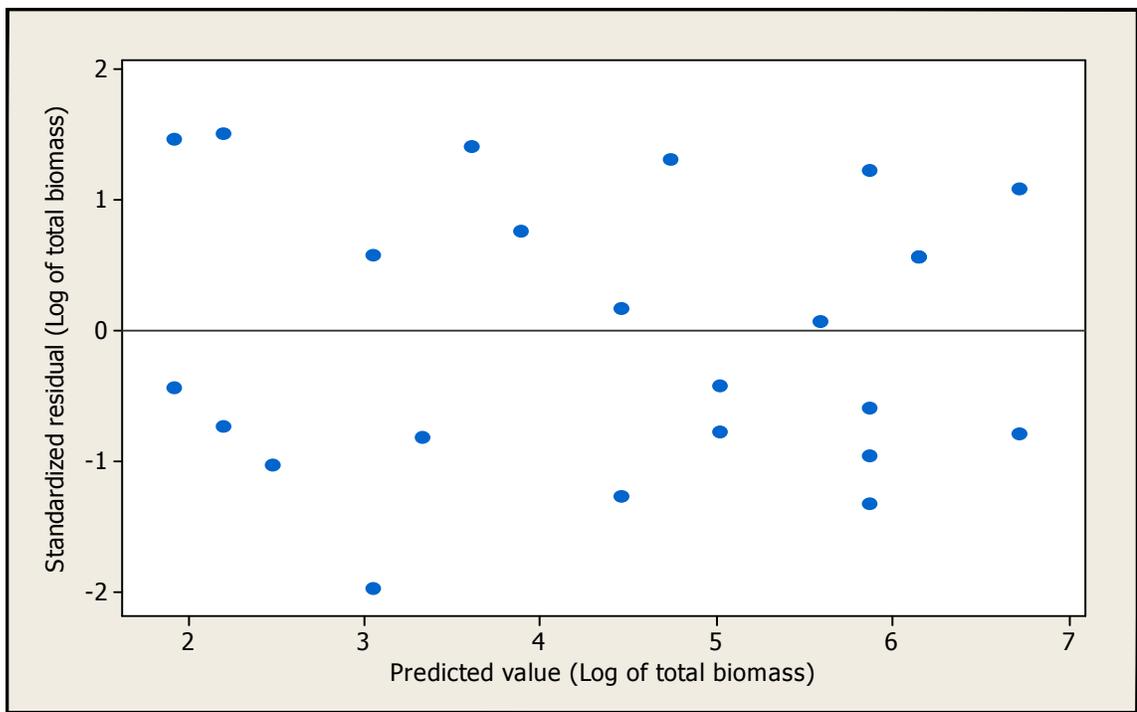
**Figure 4.28: Predicted and residual values for logarithm of total tree aboveground biomass in Sexaxa estimated by logarithm of crown diameter**

The coefficients and fit statistics from fitting the biomass prediction model (Table 4.2) indicate that the intercept and the slope for the biomass prediction model estimated by the crown diameter and the overall fit of the biomass prediction model are significantly different from zero, ($p < 0.0001$).

An examination of the residuals in Figure 4.28 shows that the predicted and residual values are randomly distributed around the zero line. There is no systematic variation in the predicted and residual values that suggests that there is an apparent rule for determining whether any particular residual is positive or negative. This indicates that the biomass prediction model provides a good fit to the data.

4.2.2.5 Biomass model for Sexaxa estimated by means of total tree height

The plot of the data together with the line of best fit showing the relationship between the total aboveground biomass and the total tree height is presented in Figure 4.29. The fitting of the biomass prediction model estimated by total tree height resulted in an R^2 of 77.9%.

The coefficients and fit statistics from fitting the biomass prediction model for the estimation of total tree aboveground biomass in Sexaxa using total tree height as the independent variable are presented in Table 4.2. The *p*-values for the intercept and the slope indicate that the constant (intercept) and the coefficient (slope) are both significantly different from zero ($p < 0.0001$). The overall fit of the biomass prediction model is also significantly different from zero ($p < 0.0001$). The *MSE* of 0.5632 reveals that there is high variability in the observations as indicated by the scatter of the observations around the line of best fit in Figure 4.29.

Figure 4.30 shows that the predicted and residual values are randomly distributed around the zero line. It will be observed from the plot in Figure 4.30 that there is no systematic variation in the predicted and residual values that suggests that there is an apparent rule for determining whether any particular residual is positive or negative. This indicates that the biomass prediction model provides a good fit to the data.
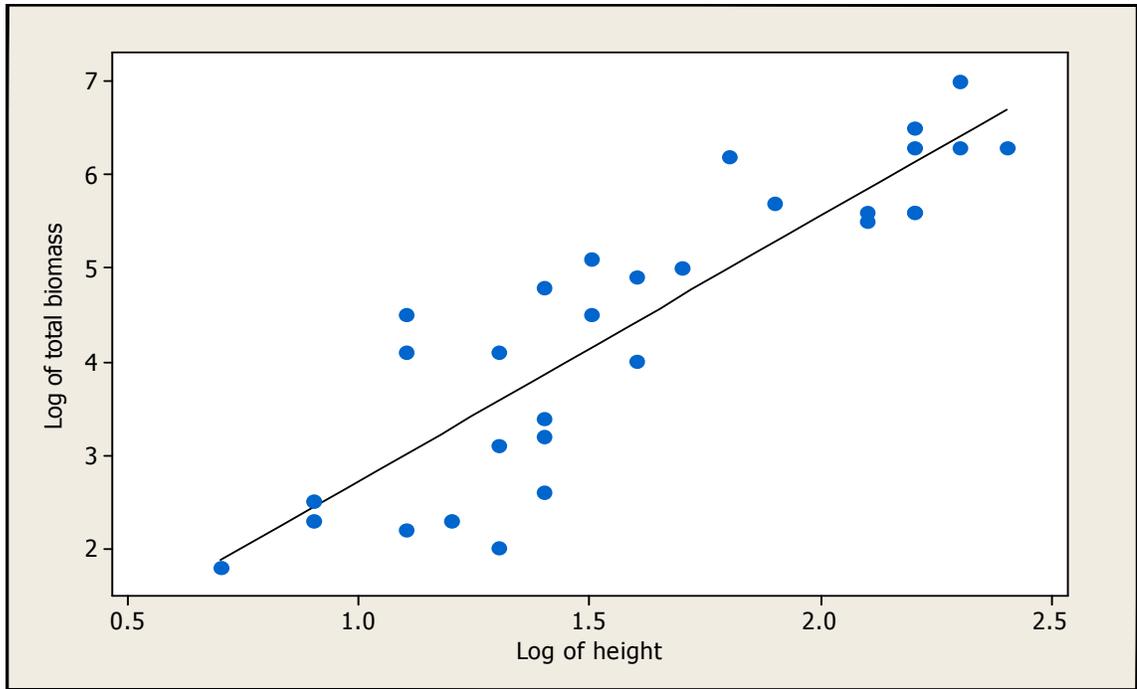
**Figure 4.29: The plot and line of best fit for logarithm of total tree aboveground biomass in Sexaxa estimated by logarithm of total tree height**
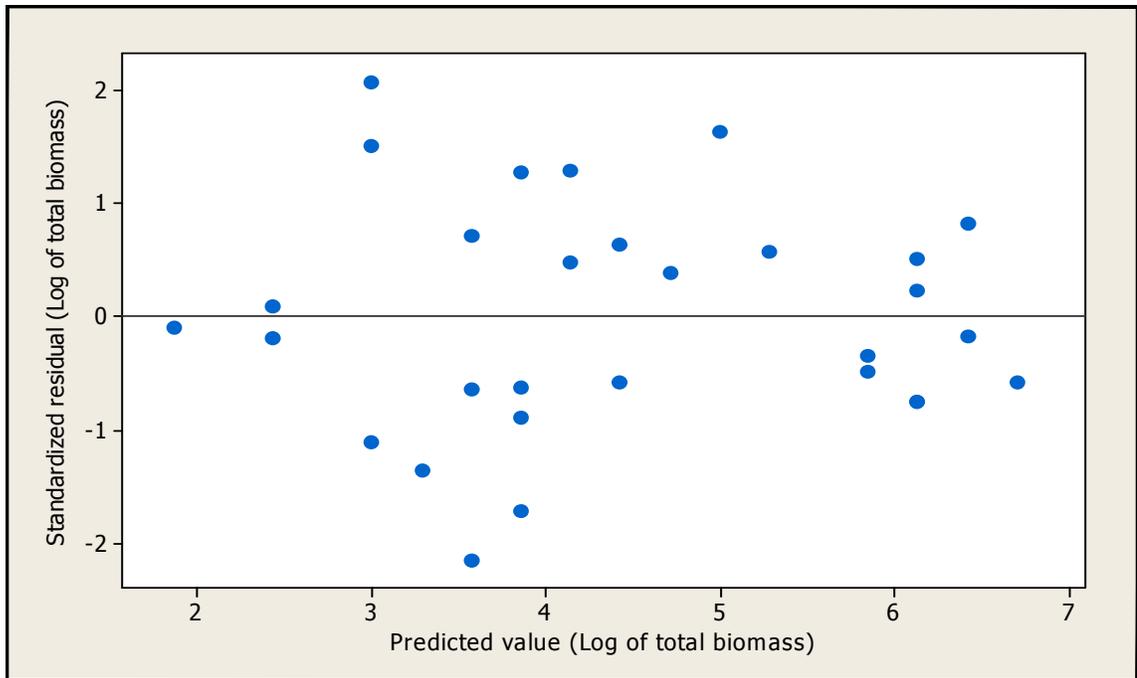
Figure 4.30: Predicted and residual values for logarithm of total tree aboveground biomass in Sexaxa estimated by logarithm of total tree height

The Bartlett's test for the equality of variances revealed that the variance is constant or equal ($p = 0.442$) at an α-level of 0.05 (Table 4.2).

The p-values for the intercept and the slope are significant ($p < 0.0001$). This confirms that there is a dependency of the dependent variable (total tree above ground biomass) on the independent variable (total tree height). The overall fit of the biomass prediction model is also significant ($p < 0.0001$) which indicates that there is a trend of the total tree above ground biomass increasing with total tree height.

4.2.2.6 Comparison of the site-specific biomass prediction models for Sexaxa

The different site-specific regression lines are shown in Figure 4.31. It will be seen from Figure 4.31 that two lines of best fit are shown for each independent variable. For each independent variable, there is the line of best fit for the linear equation and another one for the higher-order equation of the quadratic form.
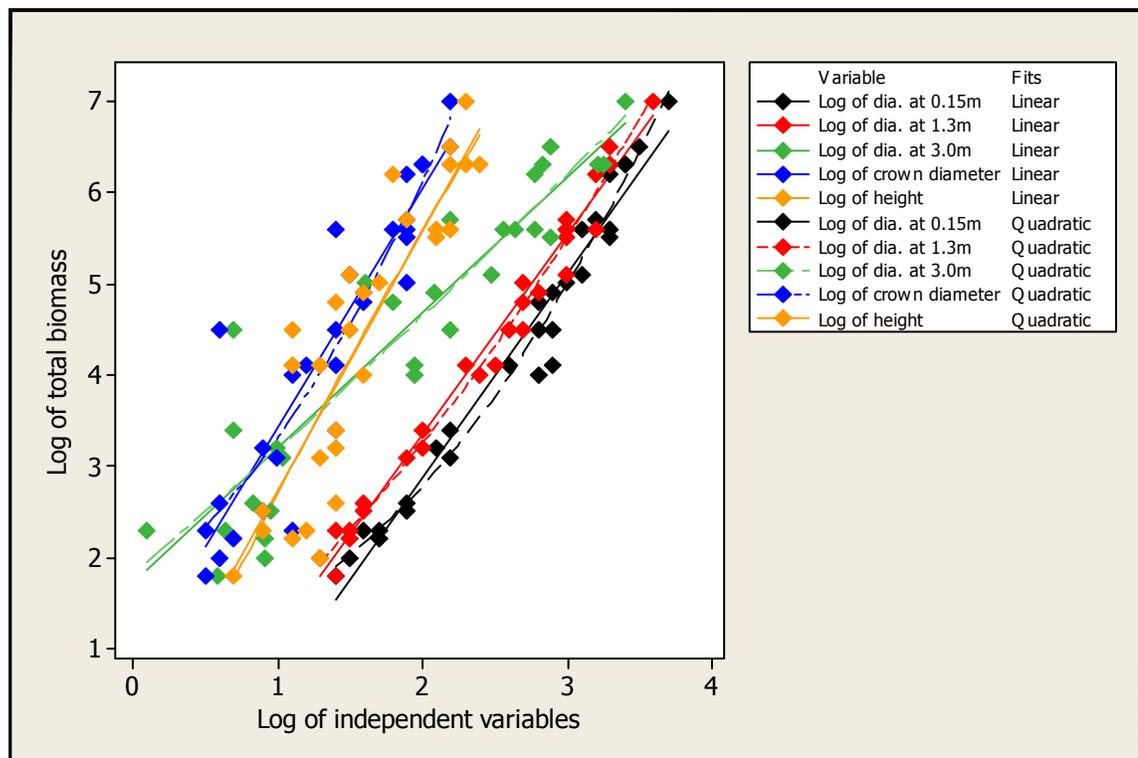
Figure 4.31: Site-specific regression lines for Sexaxa

The two lines have been included for ease of comparison. The plot of the observations and the regression lines show that the biomass prediction models that provide the best fit to the data are of the linear form, in exception of the stem diameter at 0.15 m where the biomass prediction model of the quadratic form provides the best fit to the data. The biomass prediction model that provides the best fit to the data is the one based on the stem diameter at 0.15 m while the biomass prediction model estimated by total tree height provides the least-fit to the data. The coefficients and fit statistics from fitting the biomass prediction models are shown in Table 4.2.

4.2.3 Site-specific biomass prediction models for Tamacha

The coefficients and fit statistics from fitting the site-specific biomass prediction models for the total tree aboveground biomass at the Tamacha site are presented in Table 4.3. The total tree aboveground biomass prediction models that were developed from the logarithms of the measurements for the stem diameter at 0.15 m; stem diameter at 1.3 m; stem diameter at 3 m; and the crown diameter were of the linear form $y = \beta_0 + \beta_1 x$ while the total tree aboveground biomass prediction model that was developed from the logarithm of the total tree height was of the cubic form $y = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_3 x^3$.

The Anderson-Darling normality test that was performed on the data resulted in p-values that were greater than the chosen α-level of 0.05. Thus, the null hypothesis was not rejected. There was not enough evidence to suggest that the data did not follow a normal distribution. The test for the equality of variance was also performed on the data. The p-values were greater than the α-level of 0.05. Thus, the null hypothesis was not rejected and the conclusion was that there was no difference between the variances.

The R^2 of 99.4% for the logarithm of the total tree aboveground biomass as a function of the logarithm of the stem diameter at 1.3 m is the best at the Tamacha site (Table 4.3). There is only 0.6% that is not accounted for by the regression. The high R^2 value indicates that there is an almost perfect positive linear relationship between the dependent and the independent variable.

Table 4.3: Coefficients and fit statistics from fitting prediction models for the estimation of total tree aboveground biomass in Tamacha

Dependent variable	Independent variable	Regression coefficients ± standard errors and *p*-values (in brackets)				R^2 values	*p*-values for regression model	*MSE*	Normality test *p*-values	Equality of variances *p*-values	*n*
		b_0	b_1	b_2	b_3						
ln(TTAB)	*ln(D_{0.15})*	-2.304± 0.25 (<0.0001)	2.466± 0.09 (<0.0001)			96.4	<0.0001	0.0890	0.148	0.695	30
ln(TTAB)	*ln(D_{1.3})*	-1.829± 0.14 (<0.0001)	2.429± 0.05 (<0.0001)			99.4	<0.0001	0.0150	0.161	0.174	27
ln(TTAB)	*ln(D_{3.0})*	1.331± 0.15 (<0.0001)	1.547± 0.07 (<0.0001)			97.0	<0.0001	0.0720	0.054	0.628	28
ln(TTAB)	*ln(CD)*	2.022± 0.27 (<0.0001)	-1.959± 0.18 (<0.0001)	4.618± 0.16 (<0.0001)	-1.303± 0.22 (<0.0001)	93.1	<0.0001	0.1942	0.138	0.653	28
ln(TTAB)	*ln(Ht)*	-0.024± 0.57 (<0.0001)	1.149± 0.28 (<0.0001)	0.536± 0.31 (<0.0001)		81.1	<0.0001	0.4958	0.227	0.204	30

a) *TTAB* is the total tree aboveground biomass b) $D_{0.15}$ is the stem diameter at 0.15 m c) $D_{1.3}$ is the stem diameter at 1.3 m
d) $D_{3.0}$ is the stem diameter at 3.0 m d) *CD* is the crown diameter e) *Ht* is the total tree height f) *ln* is the natural logarithm

4.2.3.1 Biomass model for Tamacha estimated by means of stem diameter at 0.15 m

The plot of the data together with the line of best showing the relationship between the logarithm of the stem diameter at 0.15 m and the logarithm of the total tree aboveground biomass at the Tamacha site are shown in Figure 4.32. The fitting of the biomass prediction model estimated by stem diameter at 0.15 m resulted in an R^2 of 96.4%. The high R^2 value (96.4%) for the biomass prediction model is confirmed by the scatter of the observations around the line of best fit in the plot of the data in Figure 4.32. The observations lie fairly close to the line of best fit which suggests that the biomass prediction model provides a good fit to the data. The narrow variance around the line of best fit is confirmed by the low *MSE* of 0.0890 (Table 4.3) for the data.
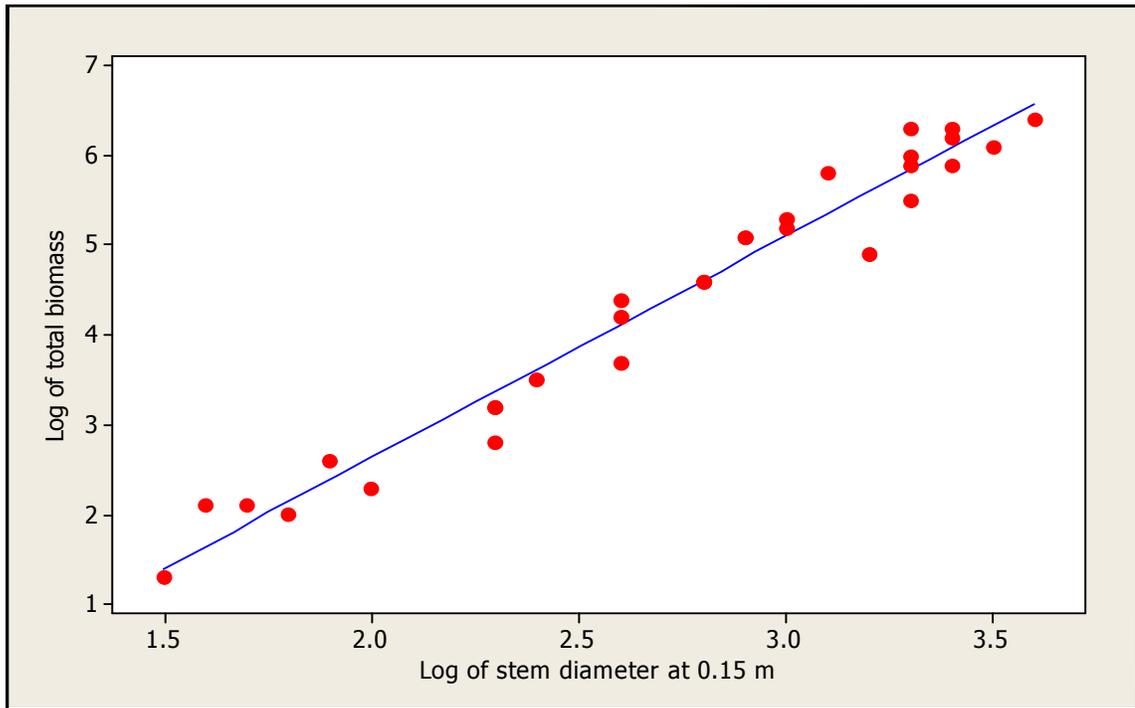
Figure 4.32: The plot and line of best fit for logarithm of total tree aboveground biomass in Tamacha estimated by logarithm of stem diameter at 0.15 m

The coefficients and fit statistics from fitting the biomass prediction model for the estimation of the logarithm of total tree aboveground biomass in Tamacha using the logarithm of the stem diameter at 0.15 m as the independent variable are presented in Table 4.3. The *p*-values for the intercept and the slope show that the constant (intercept)

and the coefficient (slope) are both significantly different from zero ($p < 0.0001$) (Table 4.3). The p-value for the overall fit of the biomass prediction model is also significant ($p < 0.0001$), which indicates that the biomass prediction model provides a good fit to the data.

The predicted and residual values for the logarithm of the total tree aboveground biomass estimated by means of the logarithm of the stem diameter at 0.15 m are shown in Figure 4.33.
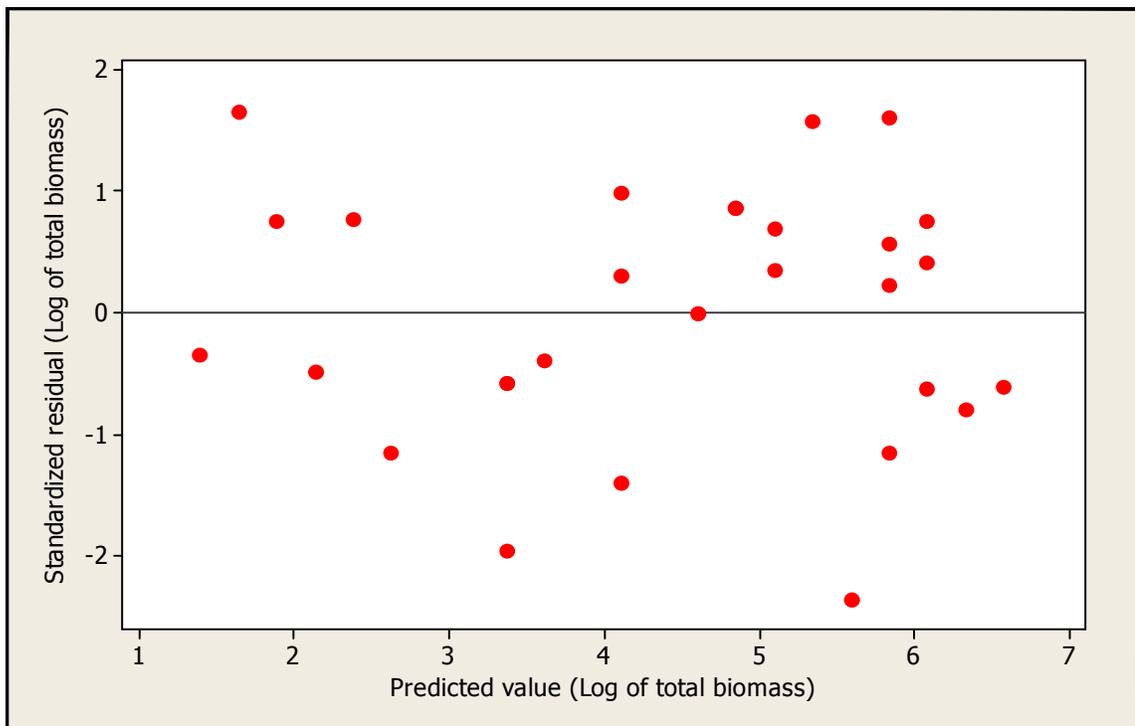
Figure 4.33: Predicted and residual values for logarithm of total tree aboveground biomass in Tamacha estimated by logarithm of stem diameter at 0.15 m

In spite of the presence of one observation which has an absolute value of less than -2 in the bottom right corner of the plot, an examination of the scatter of the residuals (Figure 4.33) shows that there is no discernible trend or pattern that could suggest that the observation was an influential observation. The diagnostic tests performed on the data did not reveal any influential observations. Therefore, no observation was excluded from the data analysis.

4.2.3.2 Biomass model for Tamacha estimated by means of stem diameter at 1.3 m

It is evident from the coefficients and fit statistics of fitting the biomass prediction model in Table 4.3 that the total tree aboveground biomass can be adequately predicted by the stem diameter at 1.3 m from the ground. However, it must be noted that three (3) observations were excluded from the data analysis after the diagnostic tests indicated that they were influential observations. Therefore, the results of fitting the biomass prediction model estimated by the stem diameter at 1.3 m are based on 27 observations.

The plot of the data together with the line of best fit estimated by means of the logarithm of the stem diameter at 1.3 m (Figure 4.34) indicated that a linear equation provided a good fit to the data because the points lie fairly close to the line of best fit and the observations do not appear to present any curvature around the line of best fit. The R^2 value for the biomass prediction model is 99.4%. This implies that only 0.6% is not accounted for by the regression.
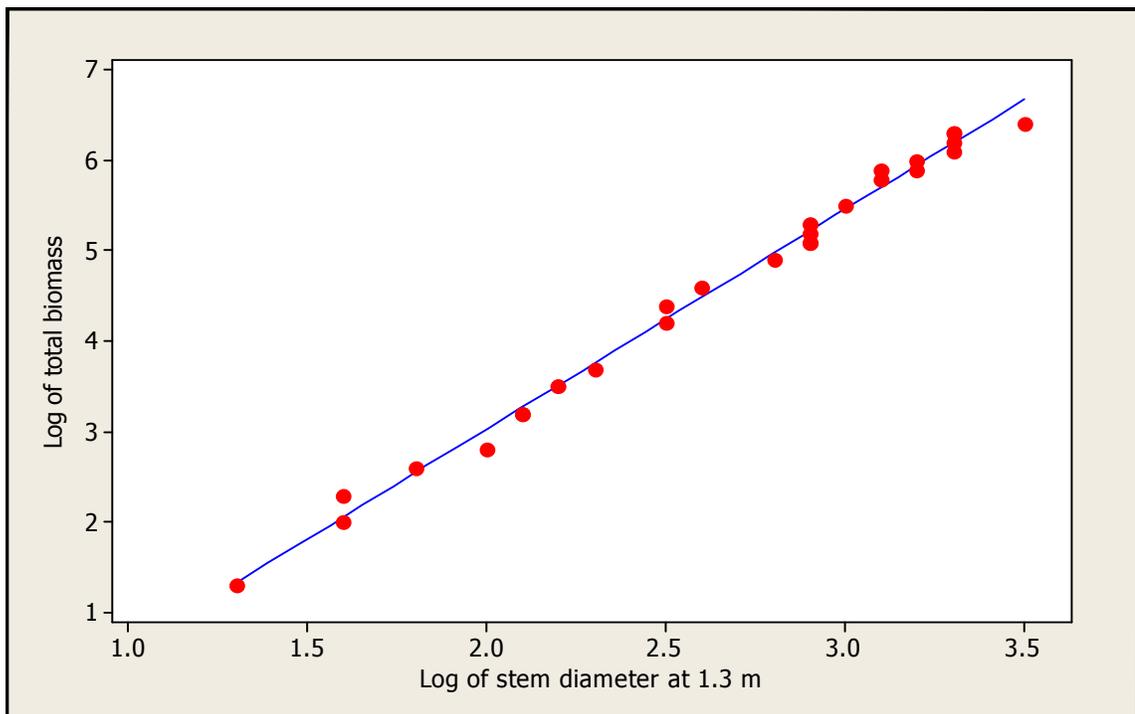
Figure 4.34: The plot and line of best fit for logarithm of total tree aboveground biomass in Tamacha estimated by logarithm of stem diameter at 1.3 m

The coefficients and fit statistics from fitting the biomass prediction model in Table 4.3 show that the intercept and the slope for the biomass prediction model estimated by the stem diameter at 1.3 m are significantly different from zero, ($p < 0.0001$). The p-value for the overall fit of the biomass prediction model is also significantly different from zero ($p < 0.0001$).

The plot of the predicted and residual values for the logarithm of total tree aboveground biomass is shown in Figure 4.35.
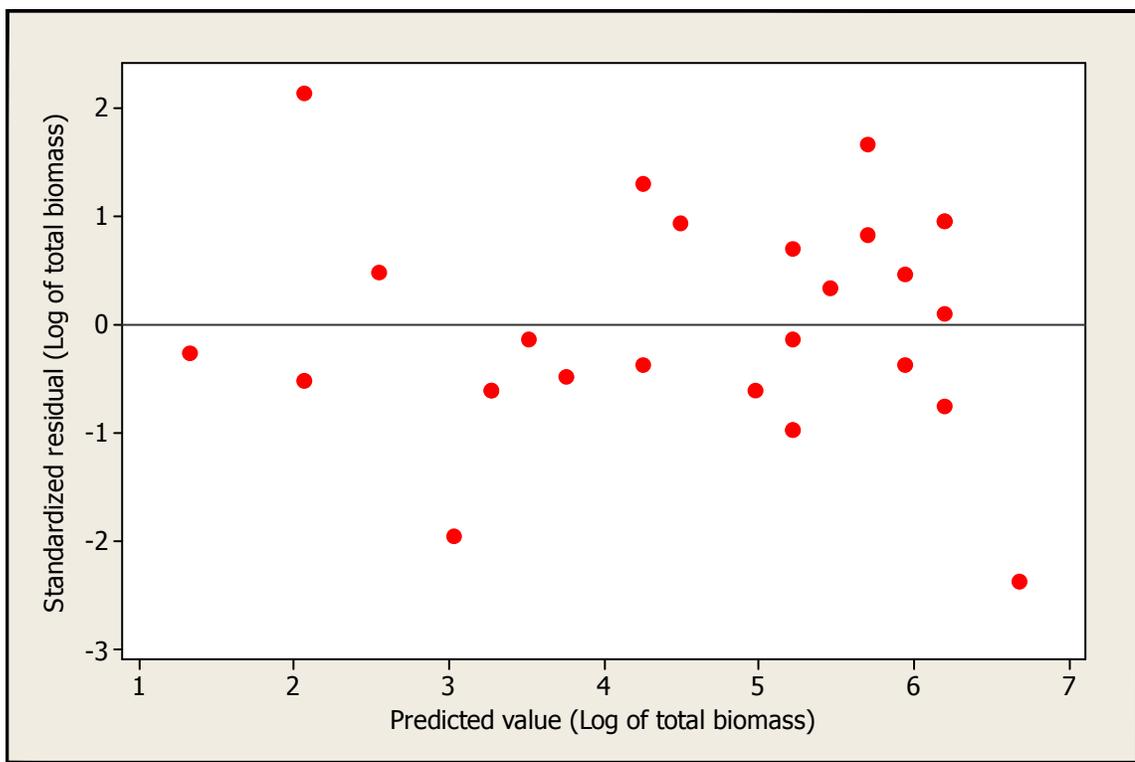
Figure 4.35: Predicted and residual values for logarithm of total tree aboveground biomass in Tamacha estimated by logarithm of stem diameter at 1.3 m

The plot in Figure 4.35 shows that the residuals fluctuated randomly around the zero line and did not show any evidence of curvature. Furthermore, the presence of two (2) observations (one in the bottom right corner and one in the top left corner of the plot) which had absolute values beyond the criterion of ±2 did not seem to influence the dependent variable (total aboveground biomass) in a systematic way. There is no

discernible trend that could suggest that the model is inadequate to predict the total aboveground biomass at stem diameter at 1.3 m. The diagnostic tests also confirmed that the observations were not influential.

The coefficients and fit statisitics from fitting the biomass prediction model indicate that the p-values for the intercept and the slope are significantly different from zero ($p <$ 0.0001) (Table 4.3). The results confirm that the total tree above ground biomass has a close relationship with the stem diameter at 1.3 m above the ground. The p-value for the biomass prediction model is also significant ($p <$ 0.0001), which indicates that the biomass prediction model provides a good fit to the data. Therefore, no additional variables are required to improve the fit of the biomass prediction model.

4.2.3.3 Biomass model for Tamacha estimated by means of stem diameter at 3 m

The plot of the data together with the line of best showing the relationship between the logarithm of the stem diameter at 3 m and the logarithm of the total tree aboveground biomass at the Tamacha site are shown in Figure 4.36.
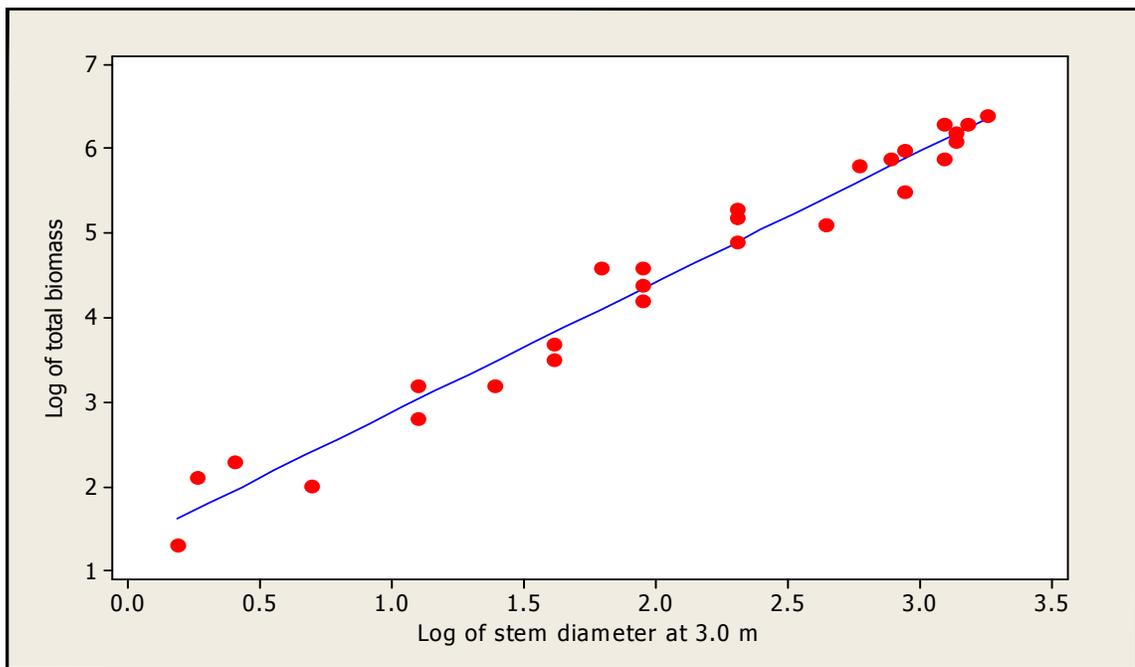

Figure 4.36: The plot and line of best fit for logarithm of total tree aboveground biomass in Tamacha estimated by logarithm of stem diameter at 3 m

The fitting of the biomass prediction model estimated by the logarithm of the stem diameter at 3 m resulted in an R^2 of 97%. The high R^2 value (96.4%) for the biomass prediction model is confirmed by the scatter of the observations around the line of best fit in the plot shown in Figure 4.34. The points lie fairly close to the line of best fit which suggests that the biomass prediction model provides a good fit to the data. The narrow variance around the line of best fit is confirmed by the low *MSE* of 0.0720 for the data. However, it must be noted that two (2) observations were excluded from the data analysis after the diagnostic tests revealed that they were influential observations.

Figure 4.37 shows that the predicted and residual values are randomly distributed around the zero line.
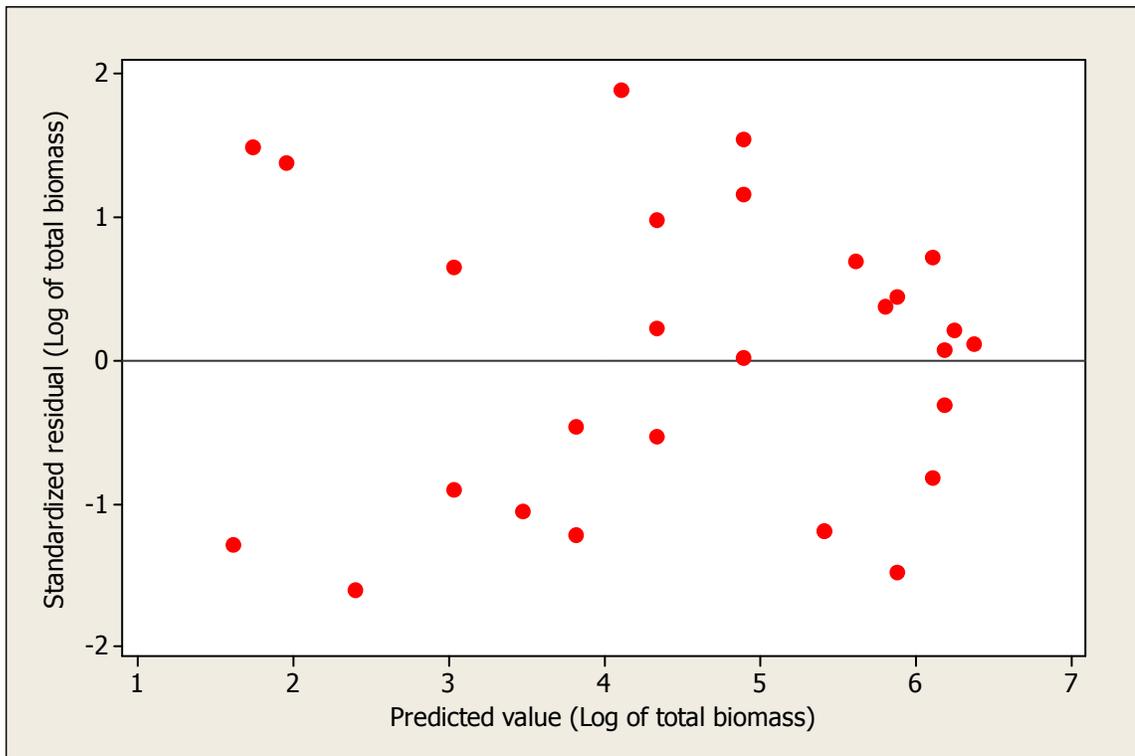
Figure 4.37: Predicted and residual values for logarithm of total tree aboveground biomass in Tamacha estimated by logarithm of stem diameter at 3 m

It will be observed from the plot in Figure 4.37 that there is no systematic variation in the predicted and residual values that suggests that there is an apparent rule for determining whether any particular residual is positive or negative. This indicates that the biomass prediction model provides a good fit to the data. The Bartlett's test for equality of variance does not suggest that the variances are inconstant or unequal ($p = 0.628$) at an α-level of 0.05 (Table 4.3).

The results from fitting the biomass prediction model indicate that the p-values for the intercept and the slope are significantly different from zero ($p < 0.0001$) (Table 4.3). The results indicate that the total tree aboveground biomass is dependent on the stem diameter at 3 m above the ground. The p-value for the regression model is also significant ($p < 0.0001$), which indicates that the biomass prediction model provides a good fit to the data.

4.2.3.4 Biomass prediction model for Tamacha estimated by crown diameter

The higher-order biomass prediction model of the cubic form for the logarithm of the total tree aboveground biomass against the logarithm of the crown diameter has accounted for 93.1% of the variability in the sample data. This indicates that total tree aboveground biomass can also be adequately predicted by crown diameter. The biomass prediction model was estimated from 28 observations because the other observations which had a standardized residual beyond the criterion of ±2 were excluded from the data analysis. The exclusion of the observations from the data analysis was made after the diagnostic tests that were performed on the data revealed that the observations had an influence on the data.

The plot of the data together with the line of best fit estimated by means of the crown diameter indicates that a cubic equation provides a good fit to the data (Figure 4.38). The observations appear to present curvature around the line of best fit and they appear to be widely scattered along the line of best fit. The wide scatter of the observations around the line of best fit is confirmed by the *MSE* of 0.1942 (Table 4.3).

The R^2 value for the biomass model was 93.1%, which just like the R^2 values for the models based on the logarithms of the stem diameter at 0.15 m; the stem diameter at 1.3 m; and the stem diameter at 3 m was very high.
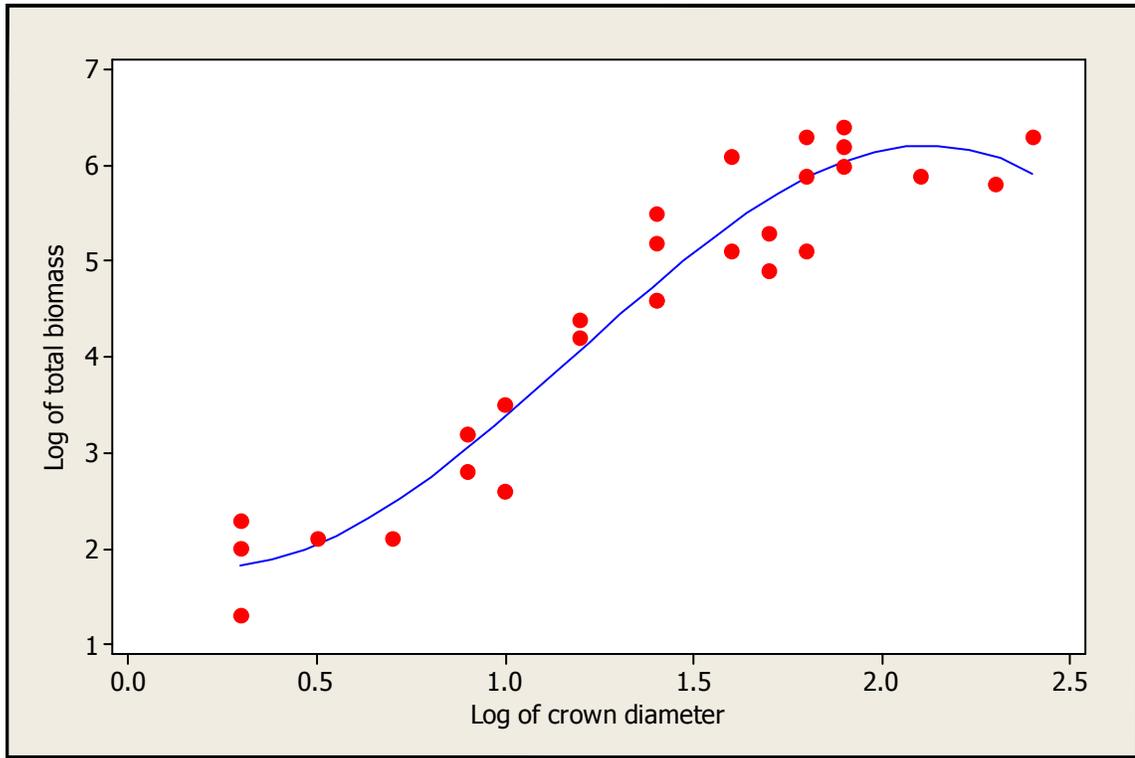

Figure 4.38: The plot and line of best fit for logarithm of total tree aboveground biomass in Tamacha estimated by logarithm of crown diameter

A complementary test of the goodness of fit that involves examining the scatter of the predicted and residual values around the zero line in Figure 4.39 indicates that there is a curved pattern of the residuals around the zero line. This pattern indicates that the non-linearity of the data and a higher-order model would provide a better fit to the data. A biomass prediction of the cubic form provided a good fit to the data.
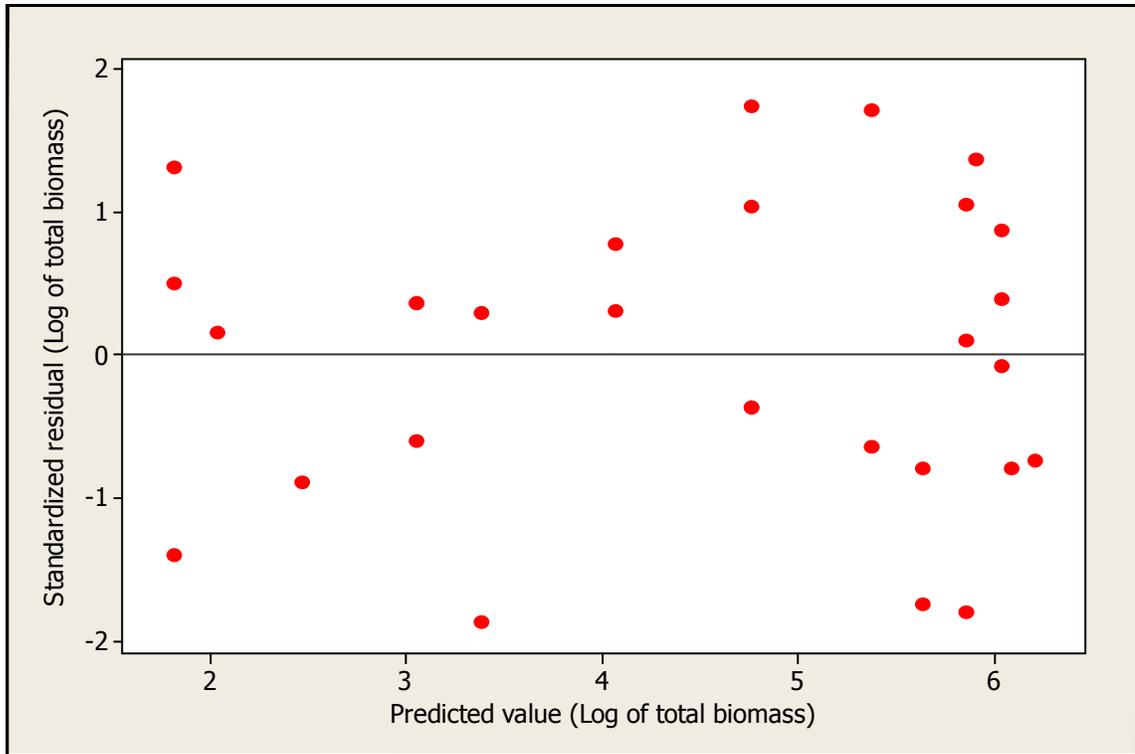
Figure 4.39: Predicted and residual values for logarithm of total tree aboveground biomass in Tamacha estimated by logarithm of crown diameter

The results from fitting the biomass prediction model indicate that the *p*-values for the intercept and the slope are significantly different from zero ($p < 0.0001$) (Table 4.3). The results indicate that there is a relationship between total tree above ground biomass and the crown diameter. The *p*-value for the overall fit of the biomass prediction model is also significant ($p < 0.0001$), which indicates that there is a dependency of the total tree above ground biomass on the crown diameter.

4.2.3.5 Biomass prediction model for Tamacha estimated by total tree height

The plot for the logarithm of the total tree aboveground biomass as estimated by the logarithm of the total tree height indicates a curvi-linear trend (Figure 4.40). Therefore, a higher-order biomass prediction model whose parameters are shown in Table 4.3 was fitted to the data. The fitting of a model of a quadratic form as opposed to the linear form resulted in coefficients that were significantly different from zero ($p < 0.0001$) and an R^2 value of 81.1%.
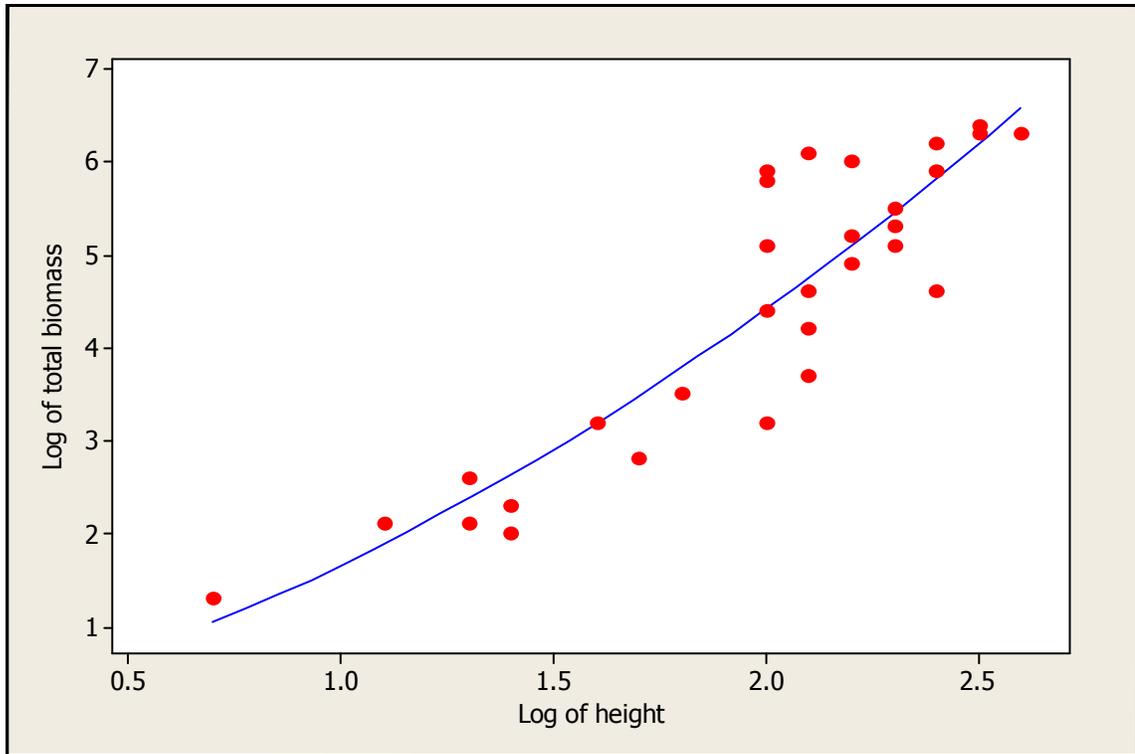
Figure 4.40: The plot and line of best fit for logarithm of total tree aboveground biomass in Tamacha estimated by logarithm of total tree height

The observations in the plot shown in the scatter plot in Figure 4.40 are widely scattered around the line of best fit with a few observations that lie far away from the line of best fit indicating outliers in the data set.

There is a curvi-linear trend in the residuals in the plot for the predicted and residual values shown in Figure 4.41. The residuals display a slight curvi-linear pattern around the zero line, which suggests that a higher-order term of the independent variable must be included in the biomass prediction model. From left to right, the residuals decrease in value and become negative (below the zero line) before gradually increasing and becoming positive again. The diagnostic tests that were performed on the data indicate that there were no influential observations.
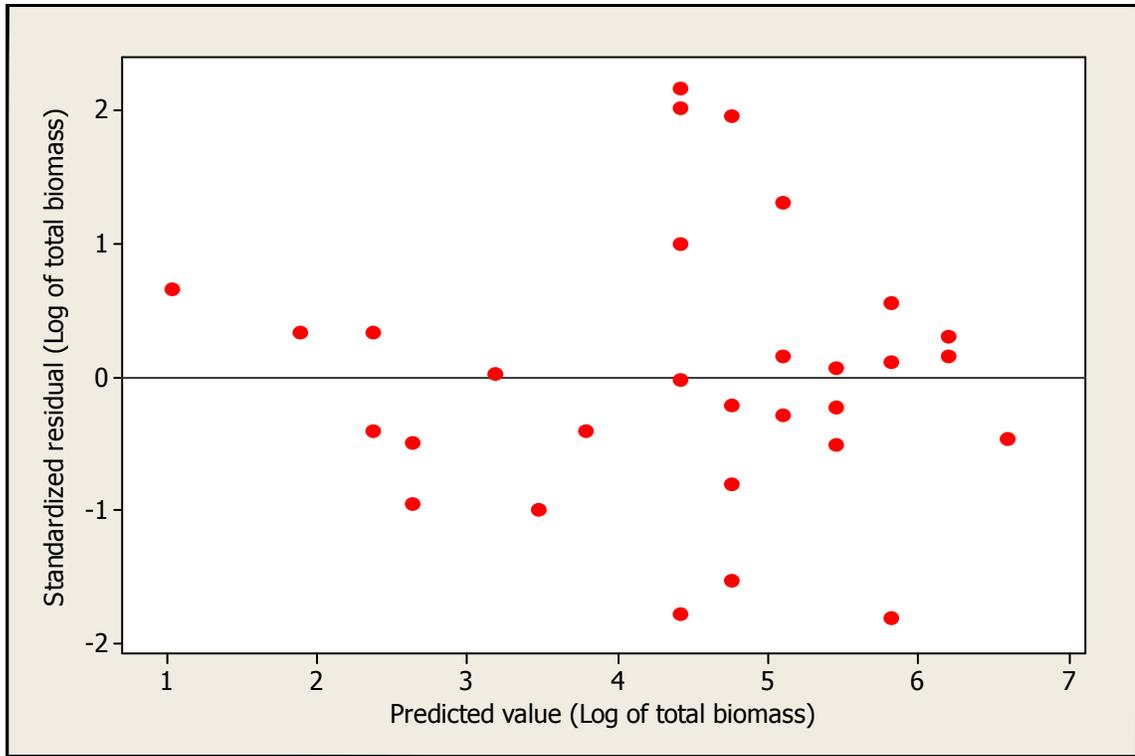
**Figure 4.41: Predicted and residual values for logarithm of total tree aboveground biomass in Tamacha estimated by logarithm of total tree height**

The coefficients and fit statistics from fitting the biomass prediction model indicate that the *p*-values for the intercept and the slope are significantly different from zero ($p <$ 0.0001) (Table 4.3). The overall fit of the biomass prediction model was also significantly different from zero ($p <$ 0.0001). The results indicate total tree aboveground biomass can be adequately predicted by fitting a higher-order biomass prediction model to the total tree height.

4.2.3.6 Comparison of the site-specific biomass prediction models for Tamacha

The different site-specific regression lines are shown in Figure 4.42. It will be seen from Figure 4.42 that three (3) lines of best fit are shown for each independent variable. For each independent variable, there is the line of best fit for the linear equation, one for the higher-order equation of the quadratic form and another one of the higher-order of the cubic form.
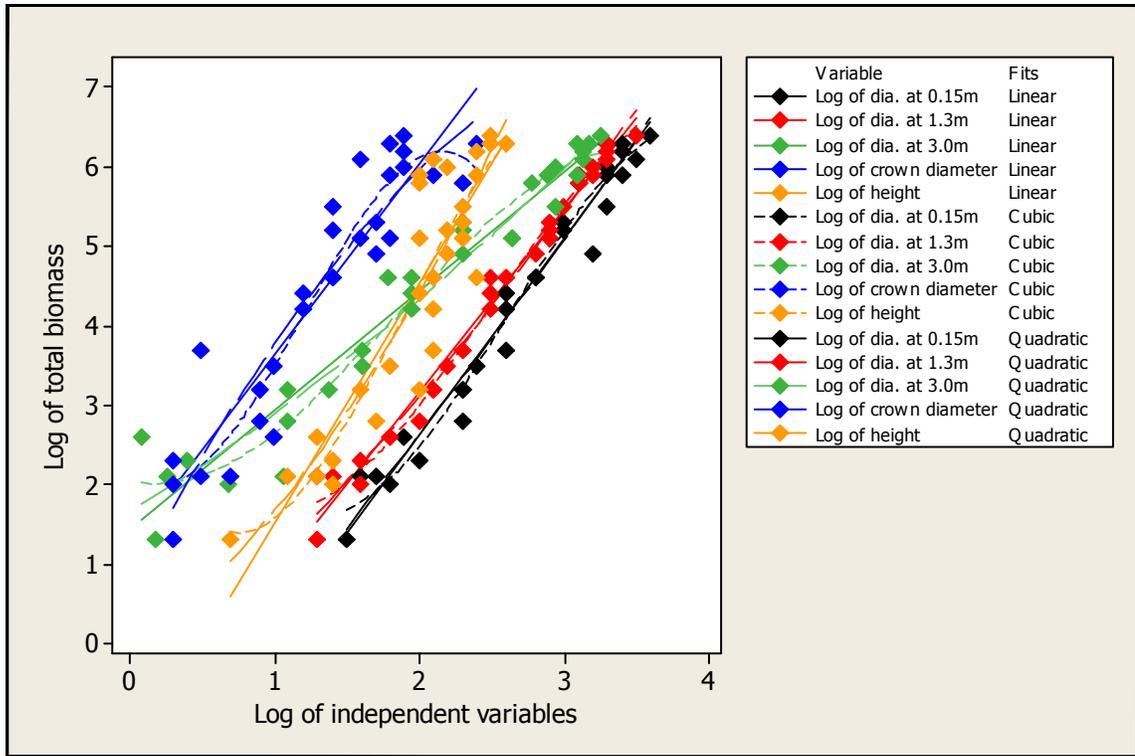
Figure 4.42: Site-specific regression lines for Tamacha

The three lines have been included for ease of comparison. The plot of the observations and the regression lines show that the biomass prediction models that provide the best fit to the data are of the linear form, in exception of the crown diameter and total tree height where the biomass prediction models of the cubic and quadratic forms provide the best fit to the data. The biomass prediction model that provides the best fit to the data is the one based on the logarithm of the stem diameter at 1.3 m while the biomass prediction model estimated by the logarithm of the total tree height provides the least-fit to the data. The coefficients and fit statistics from fitting the biomass prediction models are shown in Table 4.3.

4.2.4 Cross-site regression models

The simplest way to analyze data from the three (3) study sites would be to pool the data from all of them and derive a single regression line that best describes all the data together. Therefore, the biomass data for each independent variable in turn, were pooled and the combined data sets were used to produce a single biomass prediction model for each independent variable. The coefficients and fit statistics from fitting cross-site biomass prediction models for the estimation of total tree aboveground biomass are presented in Table 4.4.

Table 4.4: Coefficients and fit statistics from fitting cross-site prediction models for the estimation of total tree aboveground biomass

Dependent variable	Independent variable	Regression coefficients ± standard errors and *p*-values (in brackets)			R^2 values (%)	*p*-values for regression model	*MSE*	Normality test *p*-values	Equality of variances *p*-values	*n*
		b_0	b_1	b_2						
ln(TTAB)	*ln(D_{0.15})*	-1.903±0.15 (<0.0001)	2.313±0.05 (<0.0001)		96.0	<0.0001	0.090	<0.005	0.860	87
ln(TTAB)	*ln(D_{1.3})*	-1.163±0.09 (<0.0001)	2.190±0.04 (<0.0001)		97.5	<0.0001	0.050	<0.005	0.821	88
ln(TTAB)	*ln(D_{3.0})*	1.619±0.11 (<0.0001)	1.450±0.05 (<0.0001)		93.3	<0.0001	0.150	<0.005	0.320	85
ln(TTAB)	*ln(CD)*	0.822±0.16 (<0.0001)	2.631±0.11 (<0.0001)		92.0	<0.0001	0.180	<0.005	0.287	83
ln(TTAB)	*ln(Ht)*	-0.277±0.35 (<0.0001)	2.461±0.20 (<0.0001)		64.7	<0.0001	0.770	<0.005	0.604	89

a) *TTAB* is the total tree aboveground biomass   b) $D_{0.15}$ is the stem diameter at 0.15 m   c) $D_{1.3}$ is the stem diameter at 1.3 m
d) $D_{3.0}$ is the stem diameter at 3.0 m   d) *CD* is the crown diameter   e) *Ht* is the total tree height   f) *ln* is the natural logarithm

The *p*-values for the Anderson-Darling normality test are shown in Table 4.4. The *p*-values are less than the chosen α-level of 0.05. Thus, there is not enough evidence to suggest that the pooled data follow a normal distribution. This was not surprising in view of the great range of size from the smallest to the largest measurements at the three study (3) sites. This means that if all the three (3) study sites are analyzed together, one of the assumptions in regression analysis would be violated, and it therefore provides further justification for having treated each site separately. However, the coefficients and fit statistics from fitting the linear equations to the data give sufficiently good fits and adequate biomass predictions to preclude the need for further data transformation more so that the data had already been transformed to their natural logarithms.

The test for the equality of variance was also performed on the data. The *p*-values are greater than the α-level of 0.05. Thus, the null hypothesis was not rejected: there is no difference between the variances. The *p*-values for the Levene's test for equal variances are also shown in Table 4.4. The Levene's test was used instead of the Bartlett's test because the Anderson-Darling normality test indicated that there was not enough evidence to suggest that the data follow a normal distribution.

4.2.4.1 Cross-site biomass prediction model estimated by stem diameter at 0.15 m

The cross-site plot and line of best fit for the logarithm of total tree aboveground biomass estimated by the logarithm of the stem diameter at 0.15 m is presented in Figure 4.43[4]. The linear model of the pooled data for the logarithm of the total tree aboveground biomass against the pooled data for the logarithm of the stem diameter at 0.15 m above the ground has accounted for 96% of the variability in the sample data. The observations in the plot shown in Figure 4.43 are scattered very close to the line of best fit. The plot of the predicted and residual values from the pooled data for the logarithm of the total tree aboveground biomass is shown in Figure 4.44. The diagnostic tests revealed that there were no influential observations.

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[4] The different study sites in Figures 4.43 and 4.44 are identified by means of a different colour. In the legend site 1 is Serule, site 2 is Sexaxa and site 3 is Tamacha.
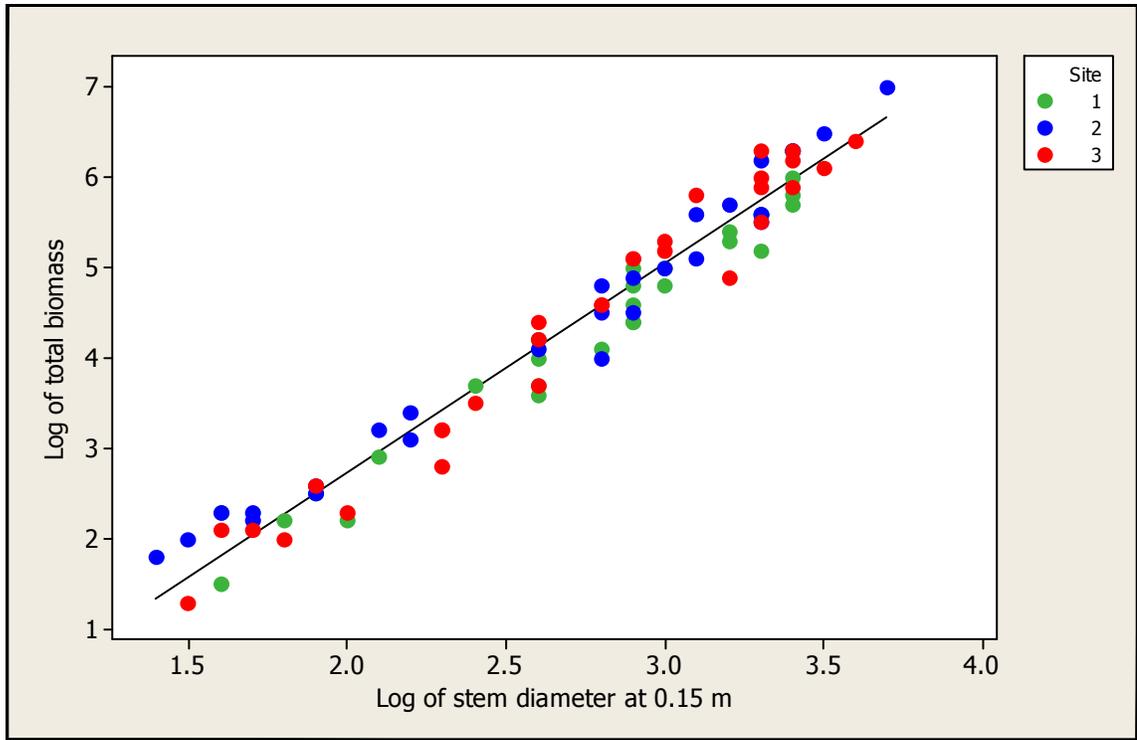
Figure 4.43: The cross-site plot and line of best fit for logarithm of total tree aboveground biomass estimated by logarithm of stem diameter at 0.15 m
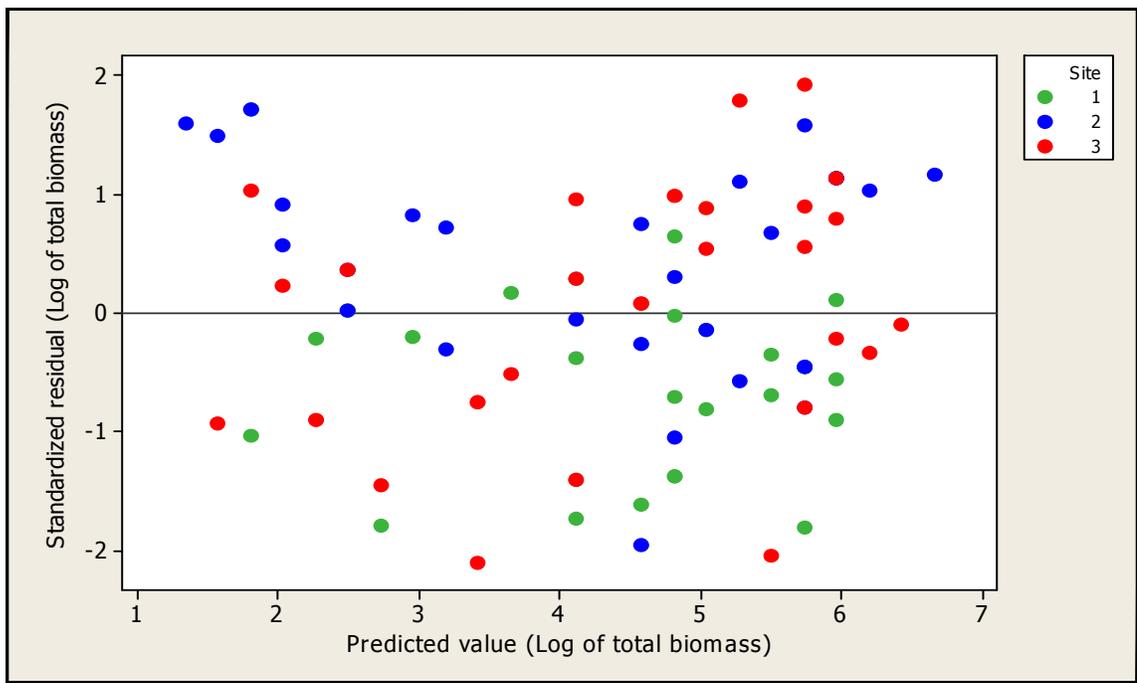
Figure 4.44: Cross-site predicted and residual values for logarithm of total tree aboveground biomass estimated by logarithm of stem diameter at 0.15 m

The good fit of the biomass prediction model to the data is also confirmed by the scatter of the residuals around the zero line as shown in Figure 4.44. The residuals are randomly scattered around the zero line and do not show that there is a discernible trend or pattern that could suggest that the model does not provide a good fit to the data.

The coefficients and fit statistics from fitting the biomass prediction model to the logarithm of the pooled data show that the p-values for the intercept and the slope are significantly different from zero ($p < 0.0001$) (Table 4.4). The p-value for the overall fit of the biomass prediction model to the pooled data is also significant ($p < 0.0001$). Thus, there is a positive linear relationship between the pooled data of the total tree aboveground biomass and the pooled data of the stem diameter at 0.15 m.

4.2.4.2 Cross-site biomass prediction model estimated by stem diameter at 1.3 m

The R^2 value of the relationship between the logarithm of the total tree aboveground biomass and the logarithm of the upper stem at 1.3 m is 97.5%. Based on the R^2 value, this is the best cross-site biomass prediction model. An R^2 value of 97.5% is very close to 100%, and it indicates that the biomass prediction model provides a good fit to the data. The diagnostic tests indicated that there were no influential observations in the data set.

This good fit that is provided by the biomass prediction model to the data is confirmed by the scatter of the observations around the line of best fit in Figure 4.45[5]. The observations are scattered very close to the line of best fit, which indicates that total tree aboveground biomass can be adequately predicted by the stem diameter at 1.3 m. The predicted and residual values in Figure 4.46 are also randomly scattered around the zero line and do not show that there is a discernible trend or pattern that could suggest that the biomass prediction model is unable to provide a good fit to the data.

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[5] The different study sites in Figures 4.45 and 4.46 are identified by means of a different colour. In the legend site 1 is Serule, site 2 is Sexaxa and site 3 is Tamacha.
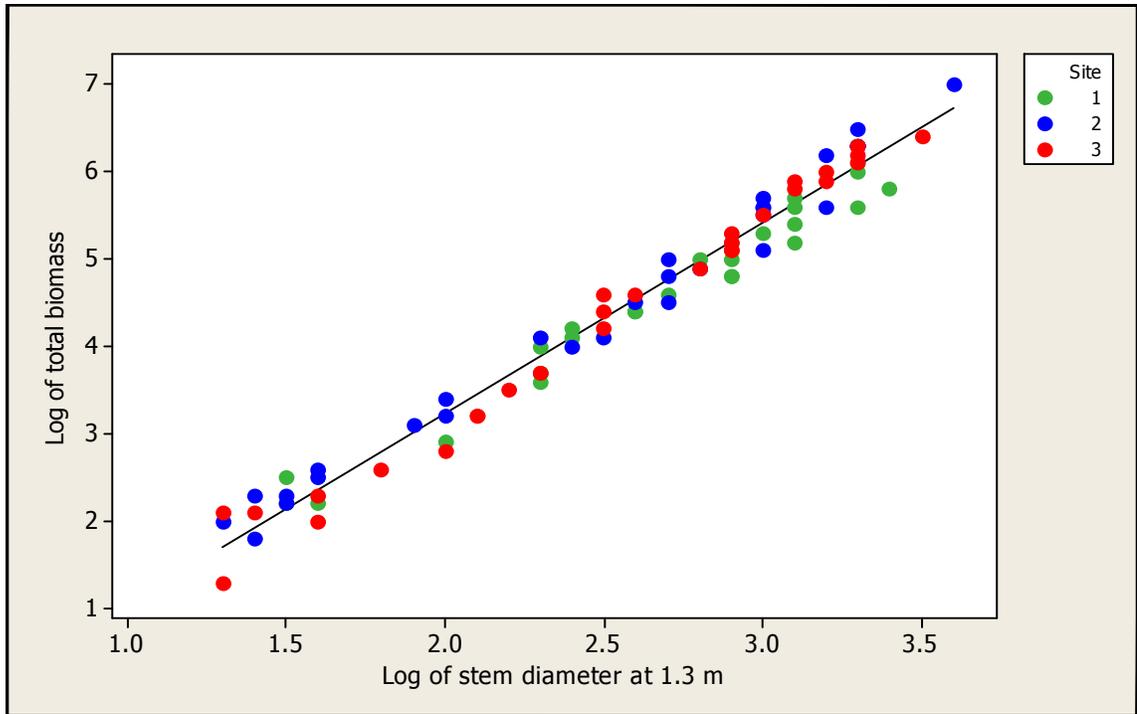
Figure 4.45: The cross-site plot and line of best fit for logarithm of total tree aboveground biomass estimated by logarithm of stem diameter at 1.3 m
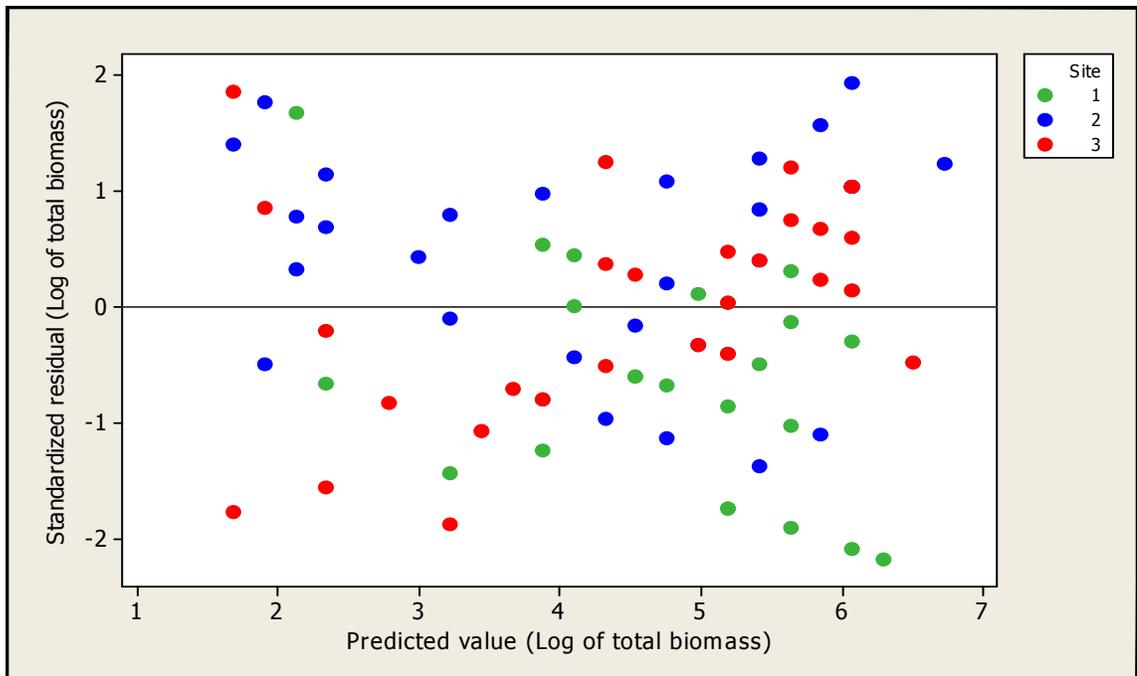
Figure 4.46: Cross-site predicted and residual values for logarithm of total tree aboveground biomass estimated by logarithm of stem diameter at 1.3 m

The coefficients and fit statistics from fitting the biomass prediction model to the pooled data show that the *p*-values for the intercept and the slope are significantly different from zero ($p < 0.0001$) (Table 4.4). The *p*-value for the overall fit of the biomass prediction model to the pooled data is also significant ($p < 0.0001$). Thus, there is a positive linear relationship between the pooled data for the logarithm of the total tree aboveground biomass and the pooled data for the logarithm of the stem diameter at 1.3 m.

4.2.4.3 Cross-site biomass prediction model estimated by stem diameter at 3 m

The cross-site plot and line of best fit for total tree aboveground biomass estimated by stem diameter at 3 m is presented in Figure 4.47[6]. The linear model of the pooled data for the logarithm of the total tree aboveground biomass against the pooled data for the logarithm of the stem diameter at 3 m above the ground has accounted for 93.3% of the variability in the sample data. The observations in the plot shown in Figure 4.47 are however widely scattered around the line of best fit. The diagnostic tests indicated that there were no influential observations.

The coefficients and fit statistics from fitting the biomass prediction model indicate that the *p*-values for the intercept and the slope are significantly different from zero ($p < 0.0001$) (Table 4.4). The *p*-value for the regression model is also significantly different from zero ($p < 0.0001$), which indicates that there is a positive linear relationship between total tree above ground biomass and the stem diameter at 3 m above the ground.

Figure 4.48 shows that the variance of the residuals tends to decrease as the predicted values increase. It will be observed from the plot in Figure 4.48 that as the predicted values increase, the residuals tend to converge towards the zero line. The convergence of the residuals towards the zero line (fanning) as the predicted values increase indicates inconstant variance. However, the Levene's test for the equality of variances revealed that the variances are constant or equal ($p = 0.320$) at an α-level of 0.05 (Table 4.4).

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[6] The different study sites in Figures 4.47 and 4.48 are identified by means of a different colour. In the legend site 1 is Serule, site 2 is Sexaxa and site 3 is Tamacha.
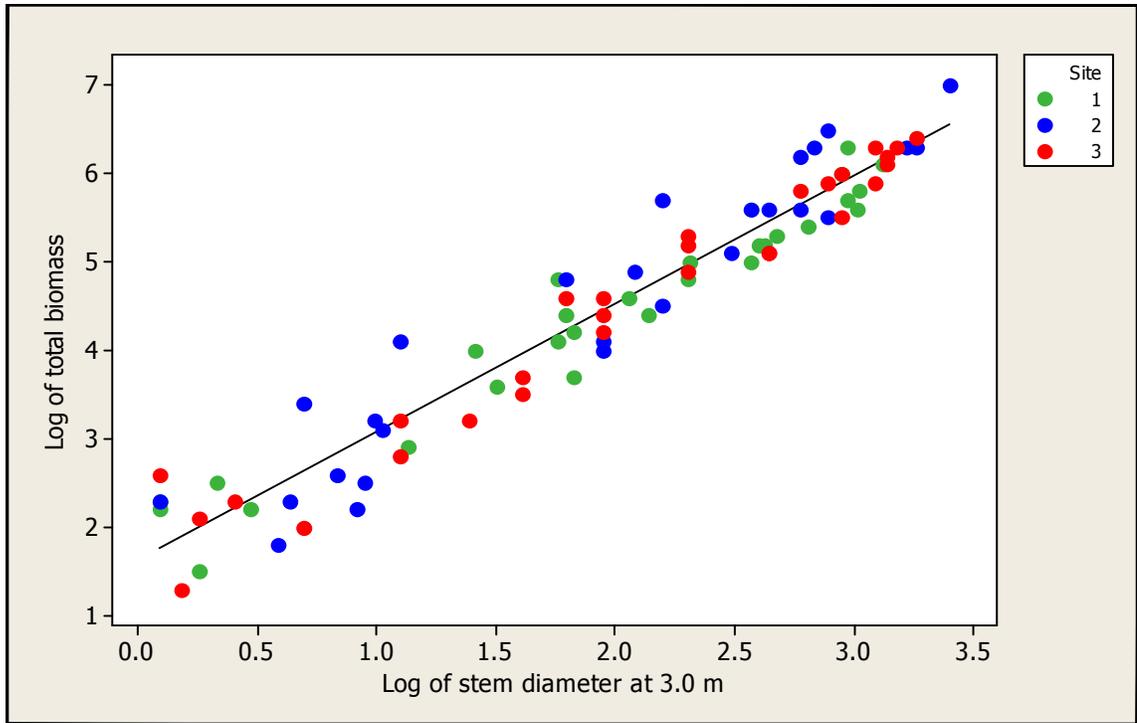
Figure 4.47: The cross-site plot and line of best fit for logarithm of total tree aboveground biomass estimated by logarithm of stem diameter at 3 m
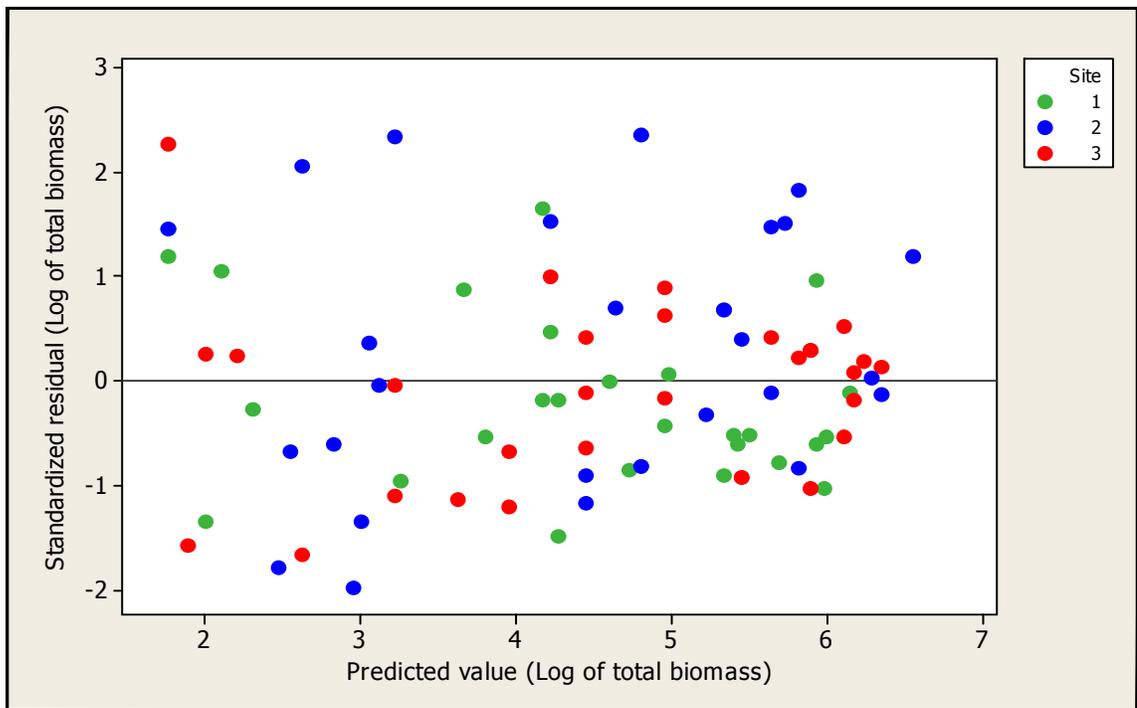
Figure 4.48: Cross-site predicted and residual values for logarithm of total tree aboveground biomass estimated by logarithm of stem diameter at 3 m

4.2.4.4 Cross-site biomass prediction model estimated by crown diameter

The linear model for the logarithm of the total tree aboveground biomass against the logarithm of the crown diameter has accounted for 92% of the variability in the sample data. Based on the high R^2 value (92%), the biomass prediction model provides a good fit to the sample data. However, the plot of the observations and line of best fit in Figure 4.49[7] shows that the observations are widely scattered around the regression line. This is indicative of the high variability in the crown diameters of the mopane trees at the study sites. The diagnostic tests indicated that there were no observations that were influential.

An examination of the residuals in the plot for the predicted and residual values of the pooled data for the total tree aboveground biomass in Figure 4.50 shows that the residuals are randomly distributed around the zero line. This is indicative of the good fit that the biomass prediction model provides to the data. There are a few outliers in the upper left corner and in the bottom right corner of the plot in Figure 4.50. The observations have smaller crown diameters when compared with the crown diameters of the other sample trees in their respective *DBH* classes; hence their classification as unusual observations. However, the diagnostic tests performed on the data set did not indicate that the observations were influential; hence their inclusion in the data analysis.

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[7] The different sites in Figures 4.49 and 4.50 are identified by means of a different colour. In the legend site 1 is Serule, site 2 is Sexaxa and site 3 is Tamacha.
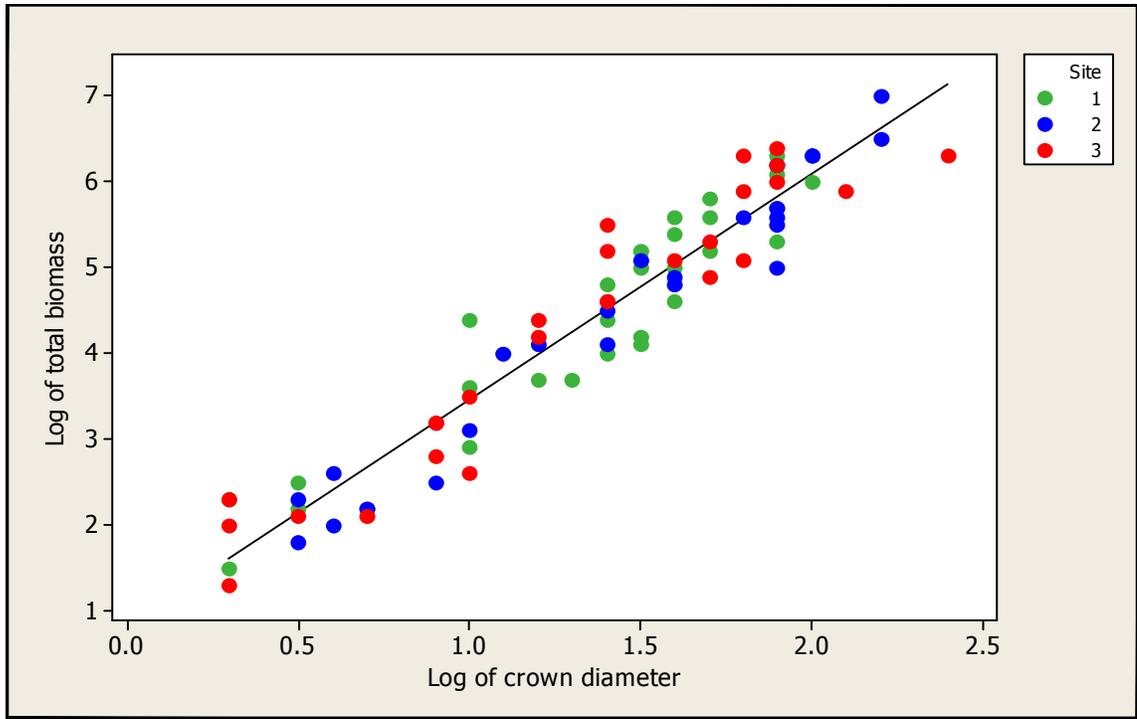
Figure 4.49: The cross-site plot and line of best fit for logarithm of total tree aboveground biomass estimated by logarithm of crown diameter
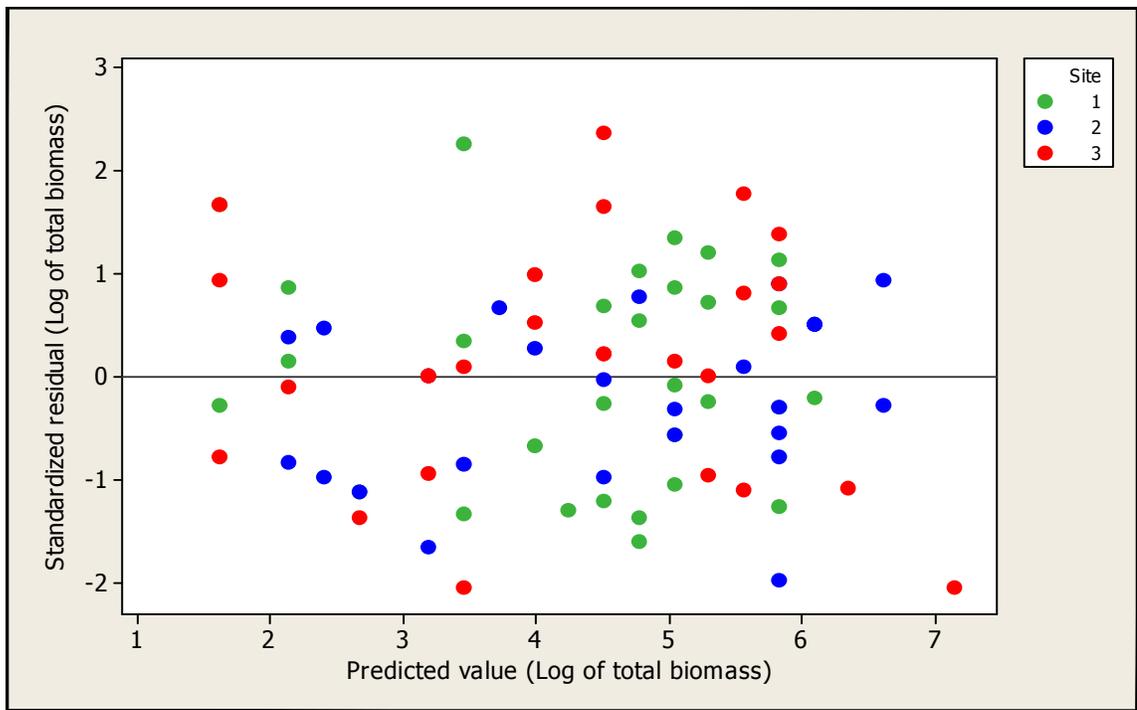
Figure 4.50: Cross-site predicted and residual values for logarithm of total tree aboveground biomass estimated by logarithm of crown diameter

The coefficients and fit statistics from fitting the biomass prediction model indicate that the p-values for the intercept and the slope are significantly different from zero ($p <$ 0.0001) (Table 4.4). The p-value for the regression model is also significantly different from zero ($p < 0.0001$), which indicates that there is a positive linear relationship between the total tree above ground biomass and the crown diameter.

4.2.4.5 Cross-site biomass prediction model estimated by total tree height

The plot and line of best fit of the pooled data for the logarithm of the total tree aboveground biomass estimated by the logarithm of the total tree height is presented in Figure 4.51. The linear model of the pooled data for the logarithm of the total tree aboveground biomass against the pooled data for the logarithm of the total tree height has accounted for 64.7% of the variability in the sample data. The observations in the plot shown in Figure 4.51[8] are however widely scattered around the line of best fit. The diagnostic tests indicated that there was no influential observation in the data set.

The plot of cross-site predicted and residual values for the logarithm of the total tree aboveground biomass is shown in Figure 4.52. The predicted and residual values in Figure 4.52 are also randomly scattered around the zero line and do not show that there is a discernible trend or pattern that could suggest that the biomass prediction model is unable to provide a good fit to the data.

The coefficients and fit statistics from fitting the biomass prediction model indicate that the p-values for the intercept and the slope are significantly different from zero ($p <$ 0.0001) (Table 4.4). The p-value for the regression model is also significantly different from zero ($p < 0.0001$), which indicates that there is a positive linear relationship between total tree above ground biomass and total tree height.

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[8] The different sites in Figures 4.51 and 4.52 are identified by means of a different colour. In the legend site 1 is Serule, site 2 is Sexaxa and site 3 is Tamacha.
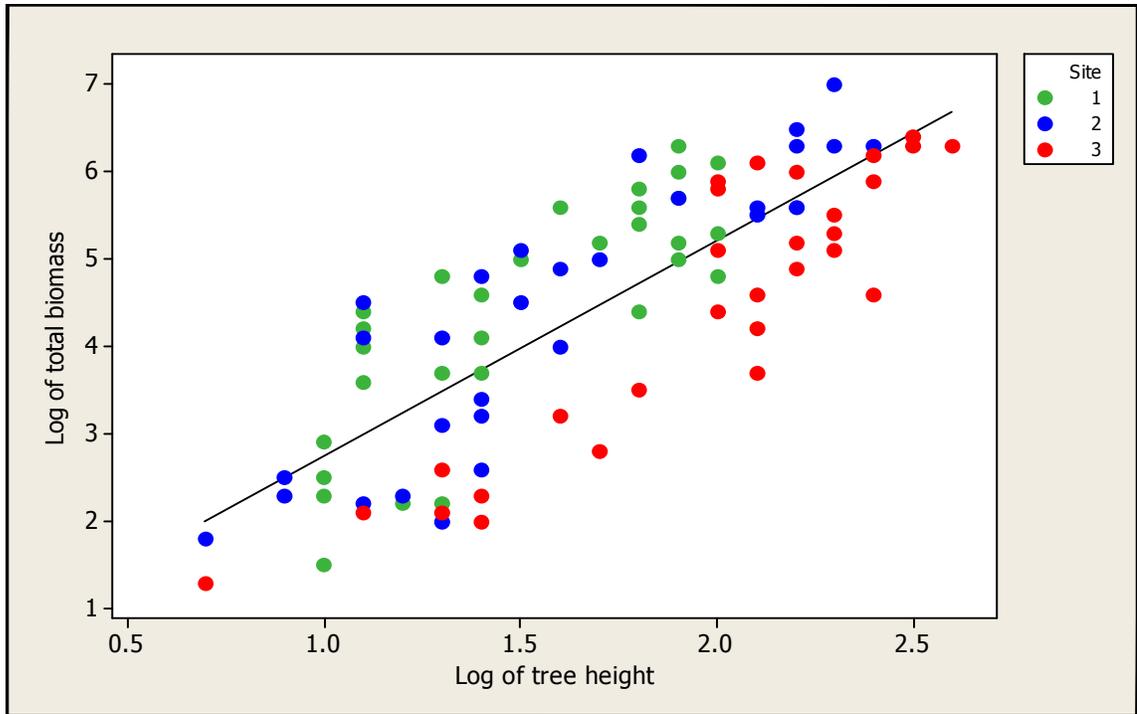
Figure 4.51: The cross-site plot and line of best fit for logarithm of total tree aboveground biomass estimated by logarithm of total tree height
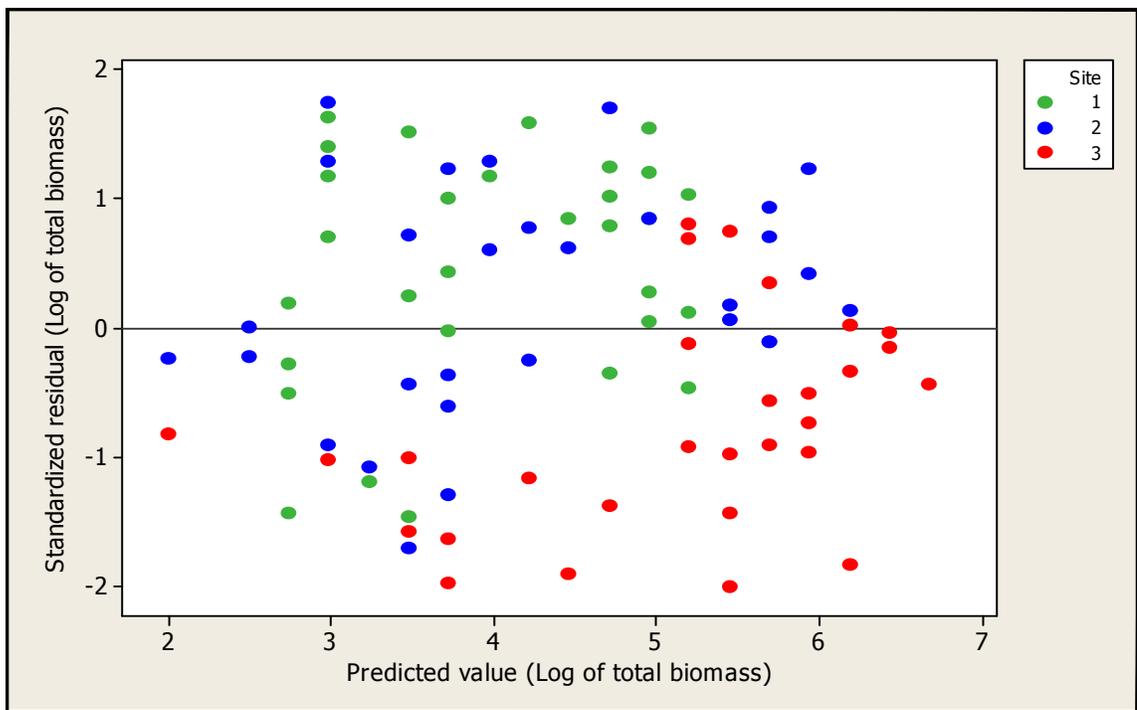

Figure 4.52: Cross-site predicted and residual values for logarithm of total tree aboveground biomass estimated by logarithm of total tree height

Figure 4.52 shows that the variance of the residuals tends to decrease as the predicted values increase. The plot in Figure 4.52 shows that as the predicted values increase, the residuals tend to converge towards the zero line. The residuals decrease as the predicted values increase in a pattern that looks like a funnel. The convergence of the residuals towards the zero line (fanning) as the predicted values increase indicates inconstant variance. However, the Levene's test for the equality of variances revealed that the variances are constant or equal ($p = 0.604$) at an α-level of 0.05 (Table 4.4).

4.2.5   Assessment of the predictive ability of the cross-site biomass models

Once the independent variables of all the destructively sampled trees were known, the coefficients in the site-specific biomass models were determined. This will allow the biomass of all the other mopane trees at that site, whose independent variables have been measured, to be predicted. Likewise, the coefficients in the cross-site biomass prediction models were determined from the pooled biomass data of mopane across the three (3) study sites in Botswana. For the pooled data set, the numbers of the sample trees did not vary. Thus, there was no need for a weighting to be attached to each site according to the number of trees representing it in the data set.

4.2.5.1 Coefficient of determination (R^2) values for the biomass prediction models

Simple calculation of the goodness of fit of the regression of the mopane across all sites is meaningless in this context, since the interest lies in detecting whether there is a loss of accuracy when compared with the site-specific biomass models. Therefore, the R^2 values obtained for the site specific regression models were compared with the R^2 values for the cross-site regression models to assess whether there was a considerable drop in the R^2 values. The R^2 values for the site-specific and cross-site biomass prediction models are shown in Figure 4.53.

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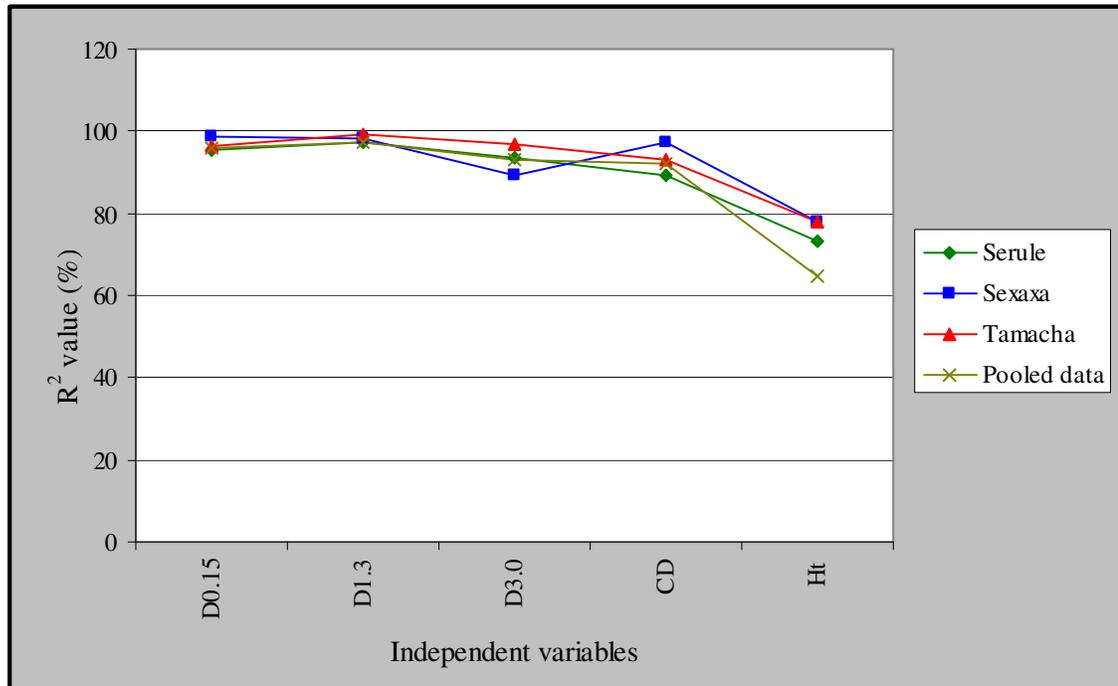
Figure 4.53: The R^2 values for the site specific and cross-site biomass prediction models

It is clear from the comparison of the R^2 values that generally, for each independent variable, the biomass prediction models resulted in comparable R^2 values. The Sexaxa site-specific biomass prediction model estimated by the logarithm of the crown diameter produced a high R^2 value while the cross-site biomass prediction model estimated by means of the logarithm of the total tree height produced a considerably lower R^2 value. However, a one-way ANOVA revealed no significant differences at the 95% confidence level (p = 0.840) between the R^2 values of the site-specific and cross-site regression models.

The R^2 values of the biomass prediction models were ranked in order to improve objectivity and ease of the assessment of the predictive ability (Table 4.5). They were ranked on a scale of 1-5 with 1 being the best and 5 being the poorest.

Table 4.5: Ranking of biomass prediction models

Independent variable	Site				Sum	Overall rank
	Serule	**Sexaxa**	**Tamacha**	**Pooled data**		
$D_{0.15}$	2	1	3	2	8	**2**
$D_{1.3}$	1	2	1	1	5	**1**
$D_{3.0}$	3	4	2	3	12	**3**
CD	4	3	4	4	15	**4**
Ht	5	5	5	5	20	**5**

The biomass prediction model based on the different points along the stem as independent variables (stem diameter at 0.15 m; stem diameter at 1.3 m; and stem diameter at 3 m) were found to have the highest rank while the crown diameter and total tree height produced the lowest ranks. The ranking in Table 4.5 shows that the cross-site biomass prediction model based on the stem diameter at 1.3 m has the highest rank followed by the cross-site biomass prediction model based on the stem diameter estimated by means of the stem diameter at 0.15 m.

4.2.5.2 Percentage of bias for the cross-site biomass prediction models

It must be noted that the R^2 value alone cannot be used to determine the goodness of fit of the biomass prediction models. The R^2 values just show the proportion of variability that has been accounted for by the regression and in general are poor criteria for model selection. Therefore, the use of the R^2 value to determine the goodness of fit has to be complemented by the use of other criteria such as the bias percentage and the standard error of estimates to determine the predictive ability of the biomass prediction models, and the testing of the significance of the slope and intercept. Therefore, in order to assess the predictive ability of the cross-site biomass prediction models, the percentage of their bias were calculated and are presented in Tables 4.6 to 4.8 and Figure 4.54.

Table 4.6: Percentage bias of cross-site models to predict total tree aboveground biomass at Serule

Independent variable	Bias (%)	Rank
$ln(D_{0.15})$	0.468	3
$ln(D_{1.3})$	0.138	1
$ln(D_{3.0})$	0.622	4
$ln(CD)$	0.384	2
$ln(Ht)$	0.811	5

Table 4.7: Percentage bias of cross-site models to predict total tree aboveground biomass at Sexaxa

Independent variable	Bias (%)	Rank
$ln(D_{0.15})$	0.338	4
$ln(D_{1.3})$	0.008	1
$ln(D_{3.0})$	-0.143	3
$ln(CD)$	0.077	2
$ln(Ht)$	-1.412	5

Table 4.8: Percentage bias of cross-site models to predict total tree aboveground biomass at Tamacha

Independent variable	Bias (%)	Rank
$ln(D_{0.15})$	-0.281	2
$ln(D_{1.3})$	-0.202	1
$ln(D_{3.0})$	-0.672	4
$ln(CD)$	-0.629	3
$ln(Ht)$	0.706	5
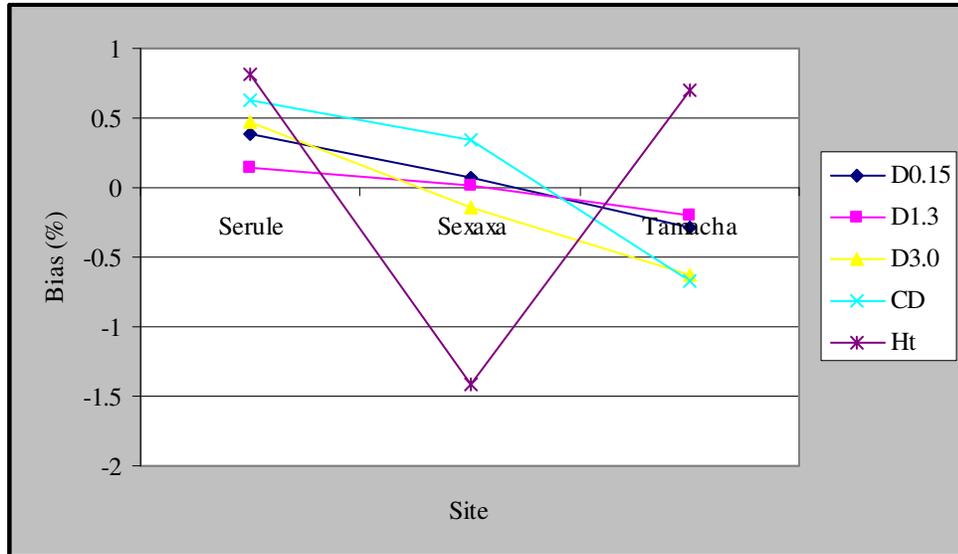
Figure 4.54: Bias (%) of the cross-site models to predict total tree aboveground biomass at the study sites

By studying the values in Table 4.6 to 4.8 and Figures 4.54 the following conclusions can be made. The prediction model based on the stem diameter at 1.3 m to predict total tree aboveground biomass is the most accurate. The other biomass prediction models based on the stem diameter at 0.15 m, stem diameter at 3 m and crown diameter show similar, but less accurate capabilities. The biomass prediction model based on total tree height is the least accurate and shows a pattern that is different from the other four (4) biomass predictions models at the Sexaxa and Tamacha sites. The biomass prediction model based on total tree height to predict total tree aboveground biomass at the Sexaxa site provides the least accurate predictive ability with a bias percentage of about -1.5 percent. This may be attributed to the highly variable total tree height of the mopane at the Sexaxa site.

4.2.5.3 Percentage of standard errors of estimates for the cross-site biomass prediction models

The standard errors of estimates were calculated and are presented in Tables 4.9 to 4.11 and Figure 4.55.

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Table 4.9: Percentage standard error of estimates of cross-site models to predict total tree aboveground biomass at Serule

Independent variable	SEE (%)	Rank
$ln(D_{0.15})$	2.606	3
$ln(D_{1.3})$	0.771	1
$ln(D_{3.0})$	3.467	4
$ln(CD)$	2.141	2
$ln(Ht)$	4.517	5

Table 4.10: Percentage standard error of estimates of cross-site models to predict total tree aboveground biomass at Sexaxa

Independent variable	SEE (%)	Rank
$ln(D_{0.15})$	2.606	3
$ln(D_{1.3})$	0.771	1
$ln(D_{3.0})$	3.467	4
$ln(CD)$	2.141	2
$ln(Ht)$	4.517	5

Table 4.11: Percentage standard error of estimates of cross-site models to predict total tree aboveground biomass at Tamacha

Independent variable	SEE (%)	Rank
$ln(D_{0.15})$	2.606	3
$ln(D_{1.3})$	0.771	1
$ln(D_{3.0})$	3.467	4
$ln(CD)$	2.141	2
$ln(Ht)$	4.517	5
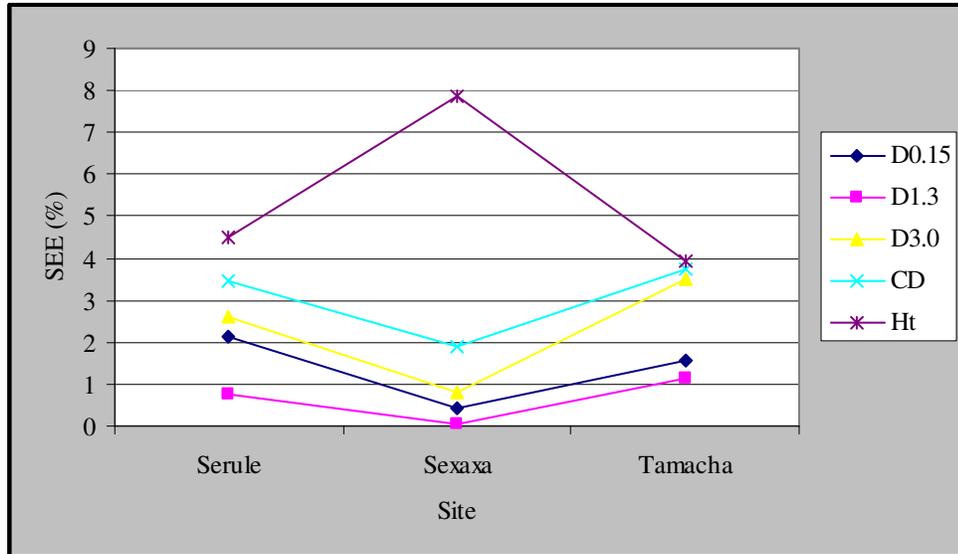
Figure 4.55: SEE (%) of the cross-site models to predict total tree aboveground biomass at the study sites

The results from Table 4.9 to 4.11 and Figures 4.55 also show that the biomass prediction model based on the stem diameter at 1.3 m to predict total tree aboveground biomass is the most accurate. The other biomass prediction models based on the stem diameter at 0.15 m, stem diameter at 3 m and crown diameter show similar, but less accurate capabilities. The results further show that the biomass prediction model based on total tree height is the least accurate and shows a pattern that is different from the other four (4) biomass predictions models at the Sexaxa and Tamacha sites. The prediction model based on total tree height to predict total tree aboveground biomass at the Sexaxa site provides the least accurate predictive ability with a standard error of estimates of about 8 percent. The results for the percentage of the standard error of estimates for the cross-site biomass prediction models are consistent with the results that show the bias percentage.

4.2.5.4 Comparison of the regression lines

A common requirement in biological experiments is the comparison of the regression lines. The analysis of covariance is best used for the comparison of the regression lines. Thus, the analysis of covariance was used to test the regression line for the cross-site

biomass prediction model based on the stem diameter at 1.3 m. The biomass prediction model based on the stem diameter at 1.3 m was tested to verify its superior performance over the other biomass prediction models and to test whether it can be used as a biomass prediction model for all the sites. The biomass prediction model that was tested is $\ln biomass = -1.163 + 2.190 \ln DBH$. The cross-site model was considered over the site-specific biomass prediction models because it would be used over as large a range of sites as possible. Therefore, it was necessary to have a biomass prediction model that has had data from a large number of sites contributing to its calculation.

The biomass prediction model was tested and interpreted as follows:
   a) Sites: significance of the difference between the intercepts;
   b) *X*: whether the slopes, if parallel, are significantly different from zero; and
   c) Sites**X*: significance of the difference between the slopes.

The analysis of covariance showed that the intercepts of the three (3) sites are not significantly different from each other because of a *p*-value that is greater than the α-level of 0.05 (*p* = 0.059). Therefore, the hypothesis that all the sites have the same intercept/origin can be accepted. The *p*-values for the slopes show that all the three sites have slopes that are not significantly different from each other (*p* = 0.061) and zero (*p* = 0.052) at the α-level of 0.05. Therefore, the two hypotheses that there is no difference in the slopes and that the slopes are not significantly different from zero can be accepted. The conclusion is that it is possible to pool the data and use the cross-site biomass prediction model based on the stem diameter at 1.3 m.

The plot of the data and the line of best fit together with the 95% confidence interval are shown in Figure 4.56. The confidence interval shows the range in which the estimated mean total tree aboveground biomass is expected to fall.
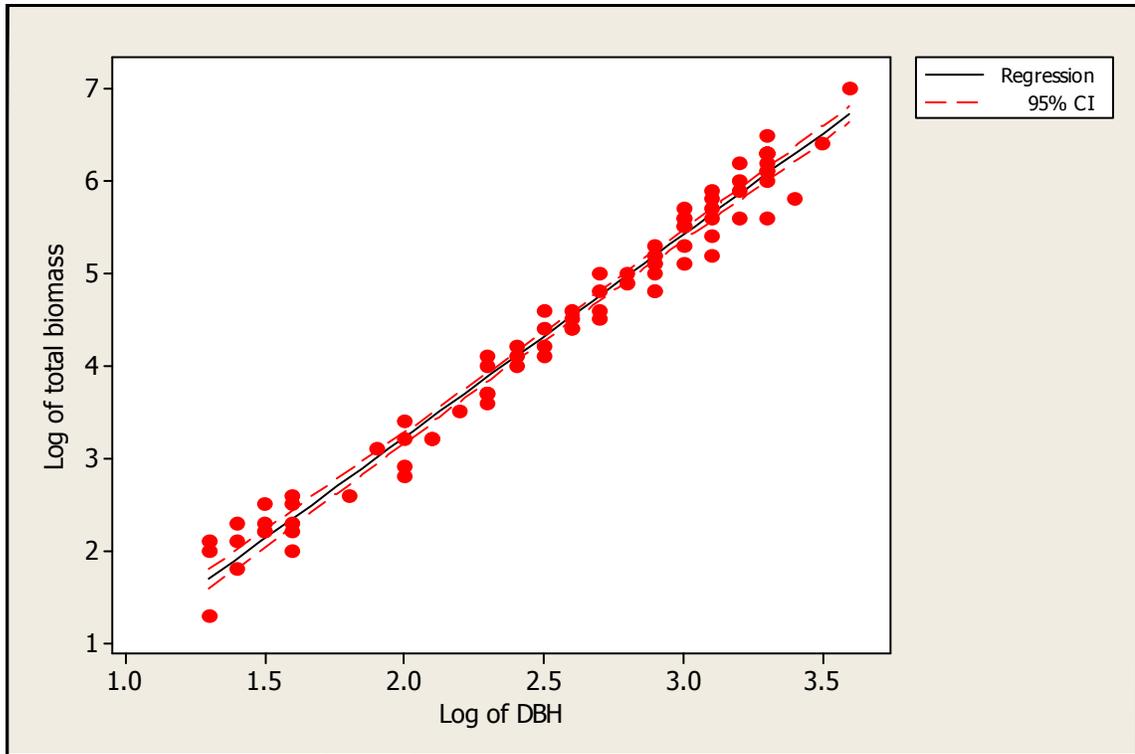
Figure 4.56: The cross-site plot and line of best fit together with the 95% confidence interval for total tree aboveground biomass estimated by logarithm of stem diameter at 1.3 m

The models developed in this study apply to mopane trees within the range of *DBH* measured (2.7 cm-35.2 cm). Extrapolation beyond the limits of the range of diameters is not recommended, since the predictions are likely to be inaccurate. The trees measured in this study represent the average range of stem sizes encountered in the mopane woodlands in Botswana. However, trees that grow much taller and reach stem diameters of 50 cm and more do occur in some parts of Botswana, but are becoming increasingly rare. Site characteristics are a determining factor in the growth of these trees (Sekhwela, 2000) and therefore, the models are also only likely to apply to mopane growing under similar conditions. Therefore, further destructive sampling over a range of different sites is needed to develop models for more widespread use.

In view of the R^2 values, the percentage of bias and the standard error of estimates, and the analysis of covariance, the stem diameter at 1.3 m provides the best fit to the data

from the individual sites and cross-sites. However, there is a marginal decrease in the R^2 value for the Serule data and the pooled data. This maybe because the trees in Serule are more variable in taper and form at or around *DBH* than those in Sexaxa and Tamacha, hence the weaker relationship between *DBH* and total tree aboveground biomass. The variability in the form may also be indicative of the level of harvesting of the mopane trees at the study sites. The mopane trees at Serule have been repeatedly cut for subsistence and commercial needs, while those at Sexaxa and Tamacha have only been exposed to a minimal level of harvesting.

Thus, where the trees have been repeatedly cut and their taper and form at and around *DBH* has become irregular, stem diameter, which is measured at a height closer to the ground level than *DBH*, may be a better reference diameter than *DBH* for predicting tree or stand characteristics (Khatry, Chhetri and Fowler, 1996). Furthermore, for low branching multi-stemmed trees such as the mopane that occurs at Serule, measuring stem diameter at ankle height is more feasible than measuring higher up the stem.

Another reason for using *DBH* as an independent variable is that in most cases it avoids problems related to buttresses and other irregularities in the shape of the stem close to the ground; and it makes measurements easy, thereby reducing costs (Hofstad, 2005).

4.2.5.5 Comparison with other existing models
In general, the stem, and in particular *DBH*, is an important predictor of total tree biomass. Tree weight (stem, branches and leaves) increases with *DBH*. Guy (1981) found similar relations in mopane woodland in Zimbabwe. Chamshama, Mugasha and Zahabu (2004) found an R^2 value of 97% in miombo woodland species in Tanzania using the model $\ln B = 0.01559 + 2.796 \ln DBH$

Where:

B = total tree biomass

DBH = stem diameter at 1.3 m from the ground

These findings suggest that *DBH* could be used as a reliable estimator of stem volume, stem weight and total weight for mopane and other species in areas of similar characteristics.

The second overall best biomass prediction model is the stem diameter at 0.15 m. Biomass prediction models that require basal or stem diameter at 30 cm above the ground level as an independent variable have been developed for some common forest types and species of the energy-deficient subsistence areas such as the middle hills of Nepal (Condori, 1985). In a mopane shrub land in northern Botswana, Tietema (1993) found an R^2 value of 95% from 36 sample trees using basal area at ankle height (5-10 cm above ground level) as an independent variable in the model $B = 0.0644BA^{1.3341}$

Where:

B = total tree biomass

BA = basal area (cm^2)

In the same study, the basal area at ankle height was used as an independent variable for 13 other fuelwood bushes and shrubs, and their R^2 values were between 80% and 95%.

In woodlands where branching of the stem below breast height is common, diameters of stump values (which are represented by the stem diameter at 0.15 m in this study) are often used. The stem diameter at 0.15 m is important as an independent variable because it represents stumps that are left behind after trees have been harvested from the woodlands. Therefore, in order to estimate the total tree aboveground biomass of the harvested trees, the stump diameters could then be used as independent variables in the allometric equations.

The third overall best independent variable is the stem diameter at 3 m. Although not the most accurate over the range of stem heights above the ground level, the relationship with total tree aboveground biomass is better in Serule and Tamacha than in Sexaxa, although very unsuitable for larger *DBH* classes. However, it should be noted that trees at the larger *DBH* classes ($\geq$ 2) fall well outside the usual spectrum of mopane shrub land like the one that occurs in Serule.

The stem component, which can be assessed independently for construction purposes, is supported by the good relationship depicted by the strong R^2 values. The relationship shows the potential for development of simple resource and product assessment

techniques for quick resource evaluation. Most of the available forestry related resource evaluation techniques relate to industrial timber, and not to community needs, and hence there are few studies which have looked at the use of such techniques to assess resource availability for community needs.

The total rank shows that crown diameter and total tree height are not as accurate as the stem to predict total tree aboveground biomass for mopane. The most probable reason is that the range of crown diameters and tree heights at the three sites is very wide. In addition, the shape of the mopane crown is irregular and highly variable at the three sites. This could be the reason why crown diameter and total tree height which have been used to predict tree biomass in other studies, (Sekhwela, 2000; Stromgaard, 1985; Stromgaard, 1986; Ter-Mikaelian and Korzukhin, 1997) are apparently inadequate to predict mopane tree fresh biomass.

Guy (1981) used total tree height as a predictor of biomass but found that separate regressions were necessary to adequately describe all the species encountered. Although prediction models that could be used to predict shrub and tree biomass from stem variables could therefore be developed, the difficulty involved in measuring shrub stem diameters and the numbers of shrubs often encountered in the field, make it tedious and time consuming to measure stem diameter. Thus, in such cases, the total tree height would be used in preference to stem diameter.

5. CONCLUSION

This work adds to the scant but growing number of studies which demonstrate good relationships between some stem characteristics and total woody biomass in mopane woodlands, from which reliable biomass tables can be developed. The biomass prediction models derived here provide an ideal opportunity for further work on the verification of woody biomass calculations, thus leading to more meaningful estimations of standing mopane wood stocks.

The purpose of this study was to develop a set of biomass prediction models that will enable the determination of total tree aboveground biomass for mopane in Botswana. The sample size of 30 trees from each of the three study sites of Serule, Sexaxa and Tamacha was distributed equally between the six *DBH* classes (5 trees per *DBH* class) that covered the range of variation of mopane at the three study sites.

There was a strong positive relationship between total tree biomass and the stem at different heights from the ground level. The strongest relationship was between the total tree aboveground biomass and the stem diameter at 1.3 m from the ground for all the three study sites and pooled data. The R^2 values of the relationships were 97.2%, 98.4%, 97% and 97.5% for Serule, Sexaxa, Tamacha and the pooled data respectively. The biomass prediction models were:

$$\ln biomass = -0.649 + 1.963 \ln DBH \quad \text{(Serule)} \tag{5.1}$$
$$\ln biomass = -1.048 + 2.189 \ln DBH \quad \text{(Sexaxa)} \tag{5.2}$$
$$\ln biomass = -1.829 + 2.429 \ln DBH \quad \text{(Tamacha)} \tag{5.3}$$
$$\ln biomass = -1.163 + 2.190 \ln DBH \quad \text{(Pooled data)} \tag{5.4}$$

In order to predict total aboveground tree biomass at all the sites the stem *DBH* would provide the most accurate estimation. Total tree height was considered to be less suitable for indirect estimation of total tree biomass. Furthermore, in both cases of the crown area and total tree height, their unsuitability to predict total tree biomass is

compounded by the difficulty of accurately determining height and crown diameters, particularly in dense populations. Moreover, crown dimensions are also influenced by stand density. However, tree height or crown dimensions may be considered for the estimation of total aboveground biomass for mopane where the mopane trees are multi-stemmed and the measurement of such stems becomes tedious. The crown dimensions can also be used in non-destructive techniques (such as in 3-D photogrammetric analysis) for the estimation of total aboveground biomass.

The models developed in this study apply to mopane trees within the range of stem diameters measured. Extrapolation beyond the limits of the range of diameters is not recommended, since the predictions could be inaccurate. The trees measured in this study represent the average range of stem sizes encountered in the mopane woodlands in Botswana. However, trees which grow much taller and reach stem diameters that are much larger than the *DBH* classes used in this study do occasionally occur in some parts of Botswana, but are becoming increasingly rare.

Site characteristics (mainly rainfall and temperature) are a determining factor in the growth of these trees (Sekhwela, 2000) and therefore, the models are also only likely to apply to mopane growing under similar conditions, therefore further destructive sampling over a range of different sites is needed to develop models for more widespread use. In spite of the differences in form and structure of the mopane at the three study sites, there are some similarities in the study sites e.g. shrub and cathedral mopane occur at all the sites. This suggests that these biomass prediction models may provide an adequate estimate of biomass for other locations, but until similar studies have been conducted in other areas, such estimates would best be regarded with a measure of caution.

Although none of the site-specific biomass prediction models, as so far determined from the results presented in this study, deviates much from the cross-site biomass prediction models, it can be concluded that in mopane woodland in Botswana, the regression of stem *DBH* (1.3 m from the ground) against the total aboveground biomass as described

by the cross-site model can be used for the determination of standing fresh total aboveground biomass of mopane trees.

Finally, the set of biomass prediction models presented here offers a realistic option of carrying out extensive surveys of standing total aboveground biomass for mopane. This will be very important in determining the effect of mopane wood harvesting, establishing stand density and mean annual increments. Another advantage is that alongside the biomass data, tree population data are also obtained. Therefore, this has an overall advantage of monitoring the long term effects of wood harvesting in the mopane woodlands and the possibility to design woodland management systems to avoid the adverse effects of wood harvesting.

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APPENDIX I

FIELD DATA COLLECTION SHEETS (Mopane biomass study)

Site: _____   **Name of Recorder:** _____

Date: _____Starting time: _____   **Finishing time:** _____

DBH **Class:** _____   **Location:** _____

Sample tree No: _____   *TTH* **(m):** _____

DBH **(cm) (1.3 m from the ground):** _____   *DAT* **(cm) (3 m from ground):** _____

DAH **(cm) (10 cm from ground):** _____   *CD* **(m):** _____+_____ = _____

Stem top diameter (cm): _____   **Stem length (m):** _____

Length of straight pole (m): _____

STEM COMPONENTS

Dbh classes	Diameters of stem (cm)			Fresh weight and length of stem					
	Bottom	Middle	Top	Billet No	Length (m)	Weight (kg)	Billet No	Length (m)	Weight (kg)
1 (≥25.1 cm)				1			1		
2 (20.1-25)				2			2		
3 (15.1-20)				3			3		
4 (10.1-15)				4			4		
5 (5.1-10)				5			5		
6 (≤5cm)				TOTALS			Totals		

STEM SAMPLE DISCS (2 cm thick)

Sample disc	Fresh weight (kg)	Dry weight (kg)
1 (*DAH:* 10 cm from ground)		
2 (*DBH:* 1.3 m from ground)		
3 (Top of stem: 3 cm diameter)		
TOTAL		

Site: _____   **Name of Recorder:** _____

Sample tree No: _____   **Location:** _____

BRANCH COMPONENTS

Branch No	Branch length (m)	Utilizable length (m)	Billet No	Billet length (m)	Weight (kg)	Branch No	Branch length (m)	Utilizable length (m)	Billet No	Billet length (m)	Weight (kg)
1			1			6			1		
			2						2		
			3						3		
			4						4		
Totals						Totals					
2			1			7			1		
			2						2		
			3						3		
			4						4		
Totals						Totals					
3			1			8			1		
			2						2		
			3						3		
			4						4		
Totals						Totals					
4			1			9			1		
			2						2		
			3						3		
			4						4		
Totals						Totals					
5			1			10			1		
			2						2		
			3						3		
			4						4		
Totals						Totals					

Site: _____   **Name of Recorder:** _____

Sample tree No: _____   **Location:** _____

BRANCH SAMPLE DISCS (2 cm thick)

Sample disc	Fresh weight (kg)	Dry weight (kg)
1		
2		
3		
TOTAL		

FOLIAGE

Billet No	Weight (kg)
1	
2	
3	
4	
TOTAL WEIGHT (KG)	

BRANCHLETS AND TWIGS (15 cm length)

Sample disc	Butt diameter (cm)	Fresh weight (kg)	Dry weight (kg)
1 (large)			
2 (intermediate)			
3 (intermediate)			
4 (small)			
TOTAL			

LEAVES (2-litre container uncompressed)

Sample No	Fresh weight of sample and cotton bag (kg)	Weight of cotton bag (kg)	Fresh weight of sample (kg)	Dry weight (kg)