UNIVERSITY OF ZULULAND

DOCTORAL THESIS

For the degree of

DOCTOR OF PHYLOSOPHY

In the field of

Agriculture/Forestry

With the title:

« **Fruit-based allometry of *Strychnos madagascariensis*, *S. spinosa*, and *Trichilia emetica* in the savanna woodlands of the Umhlabuyalingana municipality, KwaZulu-Natal, South Africa** »

FACULTY OF SCIENCE AND AGRICULTURE, DEPARTMENT OF AGRICULTURE

Candidate: ARINDO LUKAWU AKWENI

Student number: 201860898

Supervisor:

Prof. Dr. GODFREY ELIJAH ZHARARE

Period of study: 2018 – 2021

National Research Foundation | RISA Research and Innovation Support and Advancement

This work is based on the research supported wholly by the National Research Foundation of South Africa (Grant Numbers: 110900, 98716)

DECLARATION BY CANDIDATE AND SUPERVISOR

Candidate

I acknowledge that I have read and understood the University's policies and rules applicable to postgraduate research, and I certify that I have, to the best of my knowledge and belief, complied with their requirements.

I declare that this doctoral dissertation is the product of my own work and effort. I have, to the best of my knowledge and belief, acknowledged all sources of information in line with normal academic conventions.

I further certify that this research is original and that the material submitted for examination has not been submitted, either in whole or in part, for a degree at this or any other university.

Name: **ARINDO LUKAWU AKWENI** Date: September 24th, 2021

Signature:

Supervisor

I am satisfied that I have given the candidate the necessary supervision in respect of this PhD research and that it meets the University's requirements in respect of postgraduate research dissertation.

I have read and approved the final version of this doctoral dissertation and it is submitted with my consent.

Name: **GODFREY ELIJAH ZHARARE** Date: September 24th, 2021

Signature:

……………………………

ACKNOWLEDGEMENTS

This work is based on the research supported by the National Research Foundation of South Africa Grant 110900 and Grant 98716 (Domestication of indigenous plants in KwaZulu-Natal's northern district), The World Academy of Sciences (TWAS), the BEBUC scholarship program, and the *Else-Kröner-Fresenius-Stiftung* Foundation. The author thanks all the above-mentioned organizations for their financial supports.

The author also thanks Dr. Foluso Osunsanmi, Mr. Henok Nzamwita, and Mrs. Renate Bisabo for their logistic support. Special gratitude is addressed to Mrs. Botshila Eale Laetitia and Ir. Bolia Ebuma Norbert for their scientific advice.

LIST OF PAPERS RESULTING FROM THIS THESIS THAT HAVE BEEN PUBLISHED IN PEER-REVIEWED JOURNALS

Akweni AL, Sibanda S, Zharare GE, Zimudzi C. 2022. Deriving biomass allocation and carbon stocks in fruit components of Strychnos madagascariensis (Poir.) and Strychnos spinosa (Lam.) in South Africa. *International Journal of Fruit Science* 22:1, 1-16. https://doi.org/10.1080/15538362.2021.1990188. [**Chapter 5**]

Akweni AL, Sibanda S, Zharare GE, Zimudzi C. 2021. Datasets supporting fruit components biomass and carbon stocks derivation of *Strychnos madagascariensis* and *Strychnos spinosa*. *Mendeley Data*, V1. Doi: 10.17632/xczzcyjd69.1. https://data.mendeley.com/datasets/xczzcyjd69/1. [**Chapter 5**]

Akweni AL, Zharare GE, Zimudzi C. 2021. Predicting the number of fruits and the seed biomass of *Trichilia emetica* (Vahl.) in the eastern coastal region of South Africa. *Trees*, *Forests and People* (2021): 100138. https://doi.org/10.1016/j.tfp.2021.100138. [**Chapter 7**]

Akweni AL, Sibanda S, Zharare GE, Zimudzi C. 2020. Fruit-based allometry of *Strychnos madagascariensis* and *S. spinosa* (Loganiaceae) in the savannah woodlands of the Umhlabuyalingana municipality, KwaZulu-Natal, South Africa. *Trees*, *Forests and People* 2 (2020): 100025. https://doi.org/10.1016/j.tfp.2020.100025. [**Chapter 4**]

Akweni AL, Sibanda S, Zharare GE, Zimudzi C. 2022. Estimating edible fruit biomass production in the savanna woodlands of KwaZulu-Natal, South Africa. *Forests, Trees and Livelihoods*: 2028685. https://doi.org/10.1080/14728028.2022.2028685. [**Chapter 6**]

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ANNEXURES

GENERAL ABSTRACT

Savannah woodlands of South Africa are endowed with a high diversity of fruit tree species among of which are *Strychnos madagascariensis*, *S. spinosa*, and *Trichilia emetica*, which have a potential for commercial harvest from the wild. Assessment of the profitability of harvesting their fruits and as well as informed decisions to harvest their fruits require an estimation or quantification of the yields of the fruits. However, allometric equations that enable the quantification of fruit biomass of trees from the wild are non-existent. The present study had four objectives. The first was to develop fruit-based allometric equations for *Strychnos madagascariensis* and *S. spinosa*. The second was to determine biomass allocation between fruit components of *Strychnos madagascariensis* and *Strychnos spinosa* and to derive the carbon (C) stocks sequestrated by fruits. The third was to evaluate the production potential of the Central Portions of the Umhlabuyalingana Municipality (CPUM) in terms of fruit biomass of *Strychnos madagascariensis* and *S*. *spinosa*. The fourth was to calibrate allometric equations that predict the amount of fruits and the biomass of seeds of *T. emetica*. Therefore, there were four studies done in accordance with these four objectives.

Development of fruit-based allometric equations

A total of 80 trees of *S. madagascariensis* and *S*. *spinosa* were selected by applying a stratified sampling approach according to four stem diameter classes during fruit ripening period. For each tree, the following parameters were measured: fruit biomass, diameter at breast height (DBH), canopy diameter, and total height. Six forms of the allometric models were fitted to the data using ordinary least squares method. DBH was the only appropriate variable in the prediction of the fruit biomass and explained 99.9% of the variation in fruit biomass. The simple linear regressions linking the DBH (in cm) to the total fresh fruit biomass (FB; in kg) were the best models and were expressed by (1) $FB = 1.0243 \times DBH^{1.1841}$; and (2) $FB = 1.0297 \times DBH^{1.1956}$; respectively for *Strychnos madagascariensis* and *Strychnos spinosa.*

Biomass allocation between fruit components and carbon (C) stocks sequestration by fruits

A total of 400 ripe fruits of *S. madagascariensis* and *S*. *spinosa* were harvested from trees distributed in seven plots across the UMkhanyakude district. Fruit shell and pulp were separated from seeds. Puree and juice of *S. spinosa* were separated by centrifugation and steam extraction, respectively. Moisture contents of the fruit

components were measured. For *S. madagascariensis* fruits, seeds contributed the most biomass (50.2 %), followed by the shell (30.8 %), and pulp had the least biomass (16.7 %). The loss of material was 2.3 %. For *S. spinosa*, the largest part of fruit biomass was in the shell (41.8 %), followed by puree (25.6 %), seeds (18.6 %), juice (6.2 %), and pulp (0.9 %). The loss of material was 6.9 %. Fruit dry biomass (FDB; in g) and fruit carbon stocks (CB; in g) were both related to fruit diameter (D; in cm) for *S. madagascariensis* ($FDB = 1.022 \times D^{2.492}$; $CB = 0.463 \times D^{2.539}$) and *S. spinosa* ($FDB = 1.015 \times D^{2.38}$; $CB = 0.198 \times D^{2.821}$).

Strychnos madagascariensis and S. spinosa fruit biomass potential of Central Portions of the Umhlabuyalingana Municipality (CPUM)

Field surveys of trees of *S. madagascariensis* and *S. spinosa* were conducted in eight 0.25-ha square plots following an East-West distance gradient of 1.4 km. The fruit biomass of trees was estimated using the fitted fruit-based allometric equations. ArcGIS tools were used to obtain the global fruit biomass production in the CPUM. The productivity of the CPUM was on average 935.2 ± 532 kg ha^{-1} and 1211.8 ± 971 kg ha^{-1} of fresh fruit biomass, respectively for *S. madagascariensis* and *S. spinosa*. This represented a maximum production potential of 13192.98 tons (t) and 17095.01 t of fresh fruit biomass for *S. madagascariensis* and *S. spinosa*, respectively.

Development of allometric equations to predict fruits and seed biomass of T. emetica

A total of 35 trees of *T. emetica* were selected based on seven classes of the diameter at breast height (DBH) in the Umkhanyakude district. Fruits were counted on each tree using randomized branch sampling technique. Twelve fruits were harvested per tree and were brought to the laboratory for the determination of biomass. Linear models, basing solely on DBH (in cm), were the best predictors of both the number of fruits on the trees (NF) and the fresh seed biomass (SB; in kg) of *T. emetica*. The exponential forms of the best-fit general models were: (1) $NF = 375.364 \times DBH^{1.009}$; and (2) $SB = 1.858 \times DBH^{1.009}$. The prediction tests of these models were not satisfactory. Tree size category models improved accuracy of predictions.

The above studies produced allometric equations that make it possible to quantify and predict the fruit yield of *S. madagascariensis*, *S. spinosa*, and *T. emetica* from their tree dimensions. These equations also allowed the derivation of the amount of juice, puree, nectar, or oil from the fruits. Furthermore, they helped to determine the repartition of biomass and carbon stocks within the fruit components. This study proved that, through fruit-based allometric equations, one can evalute the commercial value of savannah woodlands basing on their fruit biomass production potential.

CHAPTER 1: GENERAL INTRODUCTION

The vegetation of South Africa is divided into nine biomes (Rutherford and Westfall 1986; Vlok et al. 2003; Mucina and Rutherford 2006). The province of KwaZulu-Natal, located in the eastern part of South Africa, is dominated by five biomes which cover three vegetation types, namely: the coastal forests (Olson et al. 2001; Mucina et al. 2003), the grasslands (Matthews et al. 1999), and the savanna woodlands (Burgess et al. 2004; Jewitt 2018). The savanna woodlands and the sandy forests of KwaZulu-Natal have a high diversity of fruit-bearing tree and suffrutex species which form a major source of income and vitamin C for local communities (McKenzie 1988). The fruit tree species include the Natal apricot (*Dovyalis longispina*), the wild-medlar (*Vangueria infausta*), the green monkey orange (*Strychnos spinosa*), the black monkey orange (*Strychnos madagascariensis*), the mangosteen (*Garcinia livingstonei*), the large sour plum (*Ximenia caffra*), the wild plum (*Harpephyllum caffrum*), the Christmas bells (*Trichilia emetica*), and many others. The suffrutices include the mobola plum (*Parinari curatellifolia*), the lemon-rope (*Salacia krausii*), among others. These plant species are spread in large numbers in the province. They have a high potential for commercial harvest from the wild. The fruits such as *S. spinosa* and *G. livingstonei* are among the most preferred in the province (Nkosi et al. 2020). Their fleshy pulps contain high amounts of juice.

Strychnos species are among the most appreciated edible fruits in rural communities. In KwaZulu-Natal, *Strychnos spinosa* is ranked as the most important and multi-purpose fruit tree species. It contains valuable and edible juicy pulp. It has the potential as an industrial crop for fruit juice based products. On the other hand, *S. madagascariensis* has useful fruit pulp and seed testa which have the potential for food product development. *Strychnos* species also have a lot of medicinal properties. *Trichilia emetica* is also a multi-purpose fruit tree species which represents an important source of food. In addition, its seeds yield two kinds of oil namely mafura oil and mafura butter. The latter is edible and is preferred for its particular properties. As these species have several uses and are in large numbers in KwaZulu-Natal, they represent an important livelihood option for rural communities. This motivated their consideration in the current study.

There are two options of utilizing the plants. It is either they are harvested from the wild or are domesticated and grown in plantation. Harvesting from the wild however requires knowledge on the volumes of the fruit available and productivity of the trees. This information is essential for conducting a cost-benefit analysis of projects involving commercial harvesting of the fruits from the wild. To evaluate the volumes/amount of the required plant resources in a biome, field inventories are necessary (Savadogo et al. 2007). This requires the determination of the number of trees and their sizes. In addition, the number of mature fruits and their total weight[1] on the trees need to be determined for estimating the productivity of the trees, which is expressed as the total weight of mature fruits per fruiting season. Estimating the fruit biomass production of fruit tree species in a biome is a complex study that entails determining the fruit biomass of trees individually and then sum it. Theoretically, this must be done for all the fruit trees that are in a biome. In large expanses of savannah, it would just be time-consuming and unrealistic to evaluate the fruit biomass of fruit-bearing species. Fortunately, there are techniques that can be used to estimate the fruit biomass in a way that saves time and resources. The techniques involve correlation between variables of an organism and the correlation studies are generally refered to as allometry. In forestry, allometry is used to predict dimensions of a tree such as the biomass or volume from its parameters such as the diameter at breast height (Henry et al. 2010), the total height (Alemdag 1981; Ebuy et al. 2011), and the wood specific density (Brown et al. 1989; Chave et al. 2005). Currently, there exist several types of allometric equations depending on the forest type involved (for example pantropical allometric equations), plant species (specific allometric equations), the area (local or site-based allometric equations), and the compartment of the tree to be estimated (above-ground and below-ground allometric equations). Above-ground allometric equations are the most common. They are mathematical expressions that enable the estimations of the total above-ground biomass of trees or a forest stand. Above-ground allometric equations are restricted to the estimations of the total above-ground biomass of trees. The equations are generally developed from a restricted number of trees (Picard et al. 2012). However, if all the tree size categories are represented in datasets used to derive/generate them, the equations can give accurate estimations or predictions of the above-ground biomass of trees. Nonetheless, it is difficult to know precisely from these equations the portion of biomass allocated to each component of a tree, namely the stem, the branches, the leaves, and the fruits. Currently, fruit-based allometric equations are scarce. In savanna woodlands (Banda et al. 2006), the fruit biomass can reach 510 kg/hectare (Campbell et al. 1996), which justifies the need to

[1] Throughout this work, the term “weight” is used in its general sense and refers to the biomass.

develop fruit-based allometry for this biome. This study aims to develop fruit-based allometric equations that will enable the estimations of the fruit biomass production of *S. madagascariensis*, *S. spinosa,* and *T. emetica* in savannah woodlands in northern coastal regions of KwaZulu-Natal, and to use the equations to estimate productivity of the trees.

CHAPTER 2: LITERATURE REVIEW

2.1. The origin of “Allometry” concept

The term *allometry* was coined in 1936 by Julian Huxley and Georges Teissier (Gayon 2000). It is a old concept, first outlined by Otto Snell in 1892 and popularized by D’Arcy Thompson in 1917. In its broadest sense, allometry is a statistical study of the correlation between measurable characteristics of parts of an object and changes in its overall structure. In biology, allometry designates the relationship between changes in shape and the overall size of organisms (Szalay 1991; Gayon 2000). The correlation between the characteristics of an organism or groups of an organism is guided by four different features of allometry namely: (1) ontogenetic allometry, which refers to a relative growth in individuals from the earliest stage to maturity; (2) phylogenetic allometry, which refers to constant evolutionary growth among individual; (3) intraspecific allometry, which refers to growth and changes within a given species; and (4) interspecific allometry, which refers to the changes among related species (Gould 1966; Levinton 2001). Changes in the characteristics of an object or an organism can be time-dependent. In other words, objects or organisms may vary in size or shape as time advances. These types of features are called ‘‘dynamic’’ or ‘‘truly temporal’’ (Gould 1966). For example, ontogenic and phylogenetic allometry are dynamic features. On the other hand, changes in characteristics of an object or an organism that are not time-dependent are called ‘‘static’’. Examples of static allometry are intraspecific and interspecific allometry.

An organism can be described by quantitative or qualitative variables that represent or form identifiable patterns. Some of the variables can be linked allometrically. For example, the above-ground weight (or volume) of a tree is correlated with its size. Allometry is applied in several disciplines for quantitatively predicting a “predictive variable” or “target variable” using a set of observed variables refered to as “explanatory variables” (Picard et al. 2012). Thus, to enable the prediction, empirical data of target variables and explanatory variables are needed to produce the allometric formula required to make the prediction. Allometry has the advantage of operating in biological systems and facilitates the biometric estimation of an organism (Peters 1983; Reitz et al. 1987; Lyman 2018).

2.2. Examples of applications of allometry by disciplines

2.2.1. Zooarchaeology

Zooarchaeology is a branch of archaeology that studies faunal remains of ancient creatures. Faunal remains are the items (such as bones and shells) left behind when an animal dies. Allometry is used in zooarchaeology to describe the relationship between parameters of bones left behind by animals and their body mass. Based on the assumption that bone weight is a fixed percentage of total body weight, the use of allometric models enables the prediction of the original body mass of animals (Reitz et al. 1987). The size reconstruction through allometry is particularly important in the fishery (Jackson et al. 2018) to understand the relationships between length and body weight of fish. This can help to develop sustainable fishery management practices (Giovas et al. 2016).

Lyman (2018) applied the concepts of allometry to derive fish body size of pre-Columbian zooarchaeological assemblages spanning 5 000 years in the Lesser Antilles. The studies of Lyman (2018) linked the standard length to the body mass of zooarchaeological fish (Peters 1983). It was revealed from this study that, the sizes of zooarchaeological fish were allometrically correlated with the sizes of osteological collection of modern fish taxa. Allometry is also used in the fishery to reconstruct fish size through time and to understand the evolution of fishing techniques (Giovas et al. 2016; Thieren and Van-Neer 2016). Recently, Grouard et al. (2019) have identified pre-Columbian Caribbean fisheries and examined the interrelationships of exploitation according to size for eight fish families.

Allometry has also been successfully used to determine the season and age of death of many fishes (Hales et al. 1992; Jiménez-Cano et al. 2016). Research has proved that the allometric relationship between otolith radius and fish length; otolith length and total live weight; otolith weight and live weight; and otolith weight and fish fork length is valid within a single species. Other zooarchaeological studies used allometry to estimate the standing crop biomass of crocodiles (Platt et al. 2009) and the body mass of Proconsul (Ruff et al. 1989).

2.2.2. Pharmacology

Pharmacology is the study of interactions between a living organism and chemicals. Allometry is used as a default approach in pharmacology to assess the fate and transport of chemicals in the body. Allometry supports methods that model the transfer, metabolism, and elimination of agents in the body (Encyclopedia of Public Health 2008). Allometry is also used to estimate human pharmacokinetic parameters from pharmacokinetic parameters measured in animals. It makes use of the fact that many physiological parameters of different species can be empirically related to the relative bodyweight of the species. The pharmacokinetic parameters of most animal species are often correlated with species body weight (Kumar and Srinivas 2008). Allometry is used to formalize that relationship. Mahmood (2018) tested two allometric methods to predict the *tissue-to-plasma partition coefficient* (Kp) from a determined in-vivo volume of distribution. The proposed methods were accurate than other empirical methods with regards to their predictive performances. Byers and Sarver (2009) used allometric methods to study the evolution of drug concentration in the body following a gradient of time.

2.2.3. Anatomy and physiology

Anatomy is a branch of natural science which deals with the structural organization of organisms (Arráez-Aybar et al. 2014) whereas physiology is a scientific study of functions and mechanisms which work within a living system. Allometry is applied in anatomy to investigate the relationship between body size and parts of body size such as the brain, limb bones (Ruff 1987), muscular strength (Gajewski et al. 2011), among others. Dimensional relationships between body weight, bone length, and cross-sectional dimensions of the lower limb bones were investigated in some animals (Gorilla, Homo, Pan, Pongo, and Macaca) utilizing allometry (Ruff 1987). Cross-sectional dimensions were found to be slightly positively allometric and highly correlated with body weight.

Allometry has also been used to explore physiological and pathological differences caused by differential growth for male and female patients (Li 2018). It was established that men and women have obvious differences in body and heart weights as well as in structures of their blood vessels. Li (2018) established criteria for characterizing functions based on allometric formulations. His research provided preliminary insights into the usefulness of cardiovascular allometry. Furthermore, allometry was also applied to determine the strength profile in young female athletes from different sports and to evaluate muscular strength concerning body mass (Gajewski et al. 2011). Relationships between body mass and muscle torques in muscle groups were determined using allometric techniques.

2.2.4. Demography

There are several analogous concepts and mechanisms between cities and biological entities. Bettencourt et al. (2007) demonstrated allometric relationships between observable properties of a city and the city size. Parameters such as employment, number of inventors, crime, and spread of disease are allometrically linked with the human city population. For the animal population, the relationship between demographic parameters such as lifespan, population size, and recruitment and attributes such as body size, phylogenic affiliation, foraging guild, and social behavior are allometrically correlated.

2.2.5. Forestry

Forestry is a science of creating, conserving, managing, using, and repairing forests, woodlands, and associated resources for human and environmental benefit. Forests and woodlands are composed of trees and undergrowth of different sizes (Letouzey 1982; White 1983). There is a statistical relationship between dimensions of different parts of a tree (Gould 1966; Chambers et al. 2001). That relationship comes from the ontogenic growth of trees which is similar for all trees. Thus, the proportions between the height of a tree and its stem diameter (generally measured at 1.3 m from the ground), the tree biomass and diameter, the tree volume and diameter follow a rule that is the same for all trees living in the same conditions, from the smallest to the largest tree (Archibald and Bond 2003; Bohlman and O'Brien 2006; Dietze et al. 2008).

Allometry is used in forestry to quantify and predict the dimensions of a tree (typically its biomass and volume) from its measured parameters (Picard et al. 2012; Picard et al. 2015). The diameter, the total height of the tree (Alemdag 1981; Ebuy et al. 2011), and the wood specific density (Chave et al. 2005; Henry et al. 2010) of the tree are the most common parameters considered for the prediction of tree biomass (Brown et al. 1989; Maniatis et al. 2011). Biomass is allocated in above-ground and below-ground components of trees (Ryan et al. 2011; Kuyah et al. 2012b; Mugasha et al. 2013). The above-ground biomass is composed of the weight of all organic matter of the aerial parts of a tree. This includes the stem biomass, the branch biomass, the leave biomass, and the fruit biomass (Picard et al. 2012). The below-ground biomass is composed of the weight of the root system of a tree (Mokany et al. 2006). The biomass of a tree is linked with tree parameters by allometric equations (Gayon 2000). Allometric equations are mathematical formulas that express the relationship between the biomass of a tree and its measured dimensions.

There are two groups of allometric equations namely: pantropical equations and site-based (or local) equations. Pantropical allometric equations are generic models and are used to estimate the biomass of tropical moist forests (Chave et al. 2014). Site-based allometric equations are specific and are only used for a specific area or vegetation (Molto et al. 2012). Allometric equations can include one or more explanatory variables.

a) Above-ground allometric equations in moist tropical forest

Many researchers have developed allometric equations to estimate the above-ground biomass of moist tropical forests (Djomo et al. 2010; Ngomanda et al. 2014). Even if the validity of estimates is still questionable (Chave et al. 2014), allometric equations remain important tools for forest biomass quantification (Chave et al. 2005). Fayolle et al. (2013a) proved that local allometric equations calibrated for the Cameroon forests gave reliable biomass estimates that were not different from biomass estimates generated using pantropical equations. On the other hand, Ngomanda et al. (2014) highlighted differences in biomass estimates using pantropical allometric equations in moist and wet tropical forests. Chap2-Table 1 presents some records of above-ground allometric equations developed for moist tropical forests.

b) Above-ground allometric equations in savannah woodlands

Savannah woodlands are open and less-dense habitats of trees, shrubs, and grass. The tops of the trees may reach 18 m in height and cover 40% of the land surface (White 1983). Woodland may form a transition to shrubland under drier conditions. There exist several allometric equations developed for savannah woodlands across central and southern Africa. Most of those equations were calibrated for the estimates of the carbon storage (Pearson and Brown 2005; Chidumayo 2013). Chap2-Table 2 shows some examples of allometric equations developed in savannah woodlands.

c) Below-ground allometric equations in savannah woodlands

Allometry is also used in forestry to estimate and predict the below-ground biomass of trees. Studies on below-ground biomass are scanty and cost demanding. Most of the below-ground biomass studies were conducted in open woodlands. Two techniques are used to predict the below-ground biomass of trees namely: the *root-to-shoot ratio* (Poorter et al. 2011; Sanquetta et al. 2011) and below-ground allometric equations (Ryan et al. 2011). Chap2-Table 2 presents some below-ground allometric equations.

Chap2-Table 1: Above-ground allometric equations in moist tropical forests. AGB is the above-ground biomass (kg); D: stem diameter (in cm); H: tree height (in m); *log*: Neperian logarithmic function; N: tree sample size; σ: wood specific density (g/cm^3) and *exp*: exponential function.

References	Study area	Sample size characteristics		Allometric equations
		Diameter range (cm)	N	
Equation with D only				
Djomo et al. (2010)	Cameroon	1-148	443	$AGB = \exp(-2.1801 + 2.5624\times\log(D))$
Chave (2001)				$AGB = \exp(-2.19 + 2.54\times\log(D))$
Fayolle et al. (2013a)	Cameroon	5 -192	138	$AGB = \sigma \times \exp(-1.183+1.940\times\log(D) + 0.239\times\log(D)^2 - 0.0285\times\log(D)^3)$
Chave et al. (2005)	Pantropical	5 -	2410	$AGB = \sigma \times \exp(-1.499+2.148\times\log(D) + 0.207\times\log(D)^2 - 0.0281\times\log(D)^3)$
Chambers et al. (2001)	Pantropical	5 -	315	$AGB = \exp(-0.37+0.33\times\log(D) + 0.93\times\log(D)^2) - 0.12\times\log(D)^3$
Pearson and Brown(2005)	Pantropical			$AGB = \exp(-2.289 + 2.649\times\log(D) - 0.021\times\log(D)^2)$
Equation with D, H				
Djomo et al. (2010)	Cameroon	1-138	274	$AGB = \exp(-3.2249 + 0.9885\times\log(D^2H))$
Equation with D, H, σ				
Ngomanda et al. (2014)	Gabon	12-109	101	$AGB = \exp(-2.5680 + 0.9517\times\log(D^2H) + 1.1891\times\log(\sigma))$
Chave et al. (2005)	Pantropical	5 -	2410	$AGB = \exp(-2.977 + \log(\sigma D^2H))$
Chave et al. (2005)	Pantropical	5 -	2410	$AGB = \exp(-2.187 + 0.916\times\log(D^2\times H\times\sigma))$
Chave et al. (2014)	Pantropical	5 -	4004	$AGB = 0.0673\times(\sigma D^2H)^{0.976}$
Ebuy et al. (2011)	D.R.Congo	22-52	12	$AGB = 1.603\times(\sigma D^2H)^{0.657}$
Djomo et al. (2010)	Cameroon	1-148	443	$AGB = \exp(-2.4733 + 0.2893\times\log(D)^2 - 0.0372\times\log(D)^3 + 0.7415\times\log(D^2H)+0.2843\times\log(\sigma))$
Equation with D, σ				
Ngomanda et al. (2014)	Gabon	12-109	101	$AGB = \exp(-4.0596 + 4.0624\times\log(D) - 0.228\times\log(D)^2 + 1.4307\times\log(\boldsymbol{\sigma}))$

Chap2-Table 2: Above-ground and below-ground allometric equations in savannah woodlands. AGB is the above-ground biomass (in kg); BGB: Below-ground biomass (kg); D: stem diameter (cm); H: tree height (in m); *log*: Neperian logarithmic function; N: tree sample size; σ: wood specific density (g/cm^3) and *exp*: exponential function.

Above-ground allometric equations		
Reference	**Area**	
Kuyah et al. (2012a)	Kenya	$AGB = 0.091 \times D^{2.472}$
Mugasha et al. (2013)	Tanzania	$AGB = 0.1027 \times D^{2.480}$
Chidumayo (2013)	Zambia	$AGB = 0.0446 \times D^{2.765}$
Ryan et al. (2011)	Mozambica	$AGB = \exp(2.601 \times \log(D) - 3.629)$
Mugasha et al. (2013)	Tanzania	$AGB = 0.0763 \times D^{2.2046} \times H^{0.4918}$
Chave et al. (2005)	Africa	$AGB = \exp(-2.187 + 0.916 \times \log(D^2 \times H \times \sigma))$
Below-ground allometric equations		
Référence	**Site**	
Kuyah et al. (2012b)	Kenya	$BGB = 0.048 \times D^{2.303}$
Mugasha et al. (2013)	Tanzania	$BGB = 0.2113 \times D^{1.9838}$
Ryan et al. (2011)	Mozambica	$BGB = \exp(2.262 \times \log(D) - 3.370)$
Mugasha et al. (2013)	Tanzania	$BGB = 0.1766 \times D^{1.7844} \times H^{0.3434}$

2.3. Methods of biomass estimates and predictions

Remote sensing, LiDAR (Light Detection And Ranging) technology, and field survey are methods commonly used to estimate the biomass of trees in a biome (Shirima et al. 2011; Carreiras et al. 2013). The choice of the method depends on the surface area (Gibbs et al. 2007). At the national level, remote sensing and LiDar techniques are the most effective methods to estimate forests and trees biomass because they save time. In small-scale surfaces, field measurements are the most appropriate. In this case field surveys are done to estimate the average amount of biomass per surface area (Picard et al. 2012), which can then be used to derive biomass in larger areas.

Remote sensing methods refer to satellite optical sensors (Landsat, MODIS), images with high resolution (Ikonos, QuickBird), aerial photography, and radar sensors to identify vegetation indices using digital processing. The LiDAR techniques are popular as they penetrate through vegetation layers, right down to the ground. The LiDAR techniques use light in the form of a pulsed laser to provide a three-dimensional structure of forest canopies (Kennel et al. 2013). With LiDAR, one can obtain precise information on the total height of individual trees, the volume of their branches, and stems in wider forest areas. However, field data are needed to validate the estimations.

Field data measurements involve the direct determination of tree parameters such as stem diameter, plant height, wood specific density, and canopy diameter (Chave et al. 2005). Although field surveys are more accurate, they are costly. In moist tropical forests, field biomass measurement involves the weighing of big trees (Vieilledent et al. 2012) of which the biomass of mature trees in tropical forests can exceed 50 tons (Chave et al. 2014).

2.4. Allometry in South Africa

The use of allometry to estimate forest biomass is recent in South Africa (Phiri et al. 2015; Mensah et al. 2016) whereas in other African countries there exist several allometric equations for biomass and carbon estimates (Kuyah, et al., 2012a; Chidumayo 2013). In addition, the available allometric equations in South Africa are restricted to a few tree species. Recently, Mensah et al. (2018) scaled allometric models that linked tree height to the tree diameter for some indigenous species. Only recently, some biomass (and carbon) studies were recorded in South Africa. Phiri et al. (2015) developed local allometric equations for three species of *Eucalyptus* in South Africa. The study involved allometric equations that predicted the biomass of four tree components namely: the stem, the branches, the foliage, and the barks. Later on, Mensah et al. (2016) produced multi-species allometric equations and proved that tree species richness was positively correlated with above-ground biomass. Mensah et al. (2017) developed local allometric for some tree species in South Africa.

Chap2-Table 3: South Africa’s local allometric equations.

Reference	N	Expression	Veg
Phiri et al. (2015)	33	$\log(AGB) = -3.49 + 2.22\times\log(D) + 0.79\times\log(H)$	WC
Mensah et al. (2016)	59	$\log(AGB) = -2.69 + 0.69\times\log(P) + 0.95\times\log(D^2H) + 1.03$	MF
Mensah et al. (2017)	59	$\log(AGB) = -3.97 + 1.55\times\log(D) + 1.57\times\log(H) + 1.024$	MF

Where **AGB**: Above-ground biomass (kg), **D**: stem diameter (cm), **H**: tree total height, **log**: Neperian logarithmic function, **N**: number of sampled trees, **P**: wood specific density (g/cm^3), **Veg**: Vegetation type, **WC**: Dry West Coastal Forests, **MF**: Mistbelt Forests.

CHAPTER 3: PROBLEM STATEMENT AND AIMS OF THE STUDY

3.1. Problem statement

Trichilia emetica, *Strychnos madagascariensis*, *and Strychnos spinosa* are indigenous fruit tree species that are widely distributed in the north coastal region of KwaZulu-Natal province. They have been identified to have potential for commercial harvesting of their fruits from the wild for vegetative oil extraction. However, it is currently difficult to estimate the amount of fruits that can be obtained from these species in the wild because fruit-based allometric equations relevant for these species are not available. It is therefore difficult to plan a harvest of the fruits. In addition, the lack of fruit-based allometric equations makes it impossible to evaluate the commercial value of savannah woodlands in terms of their potential to produce fruit biomass. Apart from the study of Murray (1927) and that of Peters et al. (1988) that pioneered the fruit-based allometry of temperate plant species, no further studies have been undertaken for wild tropical fruit tree species. Because the savannah woodlands of KwaZulu-Natal are widely endowed with fruit tree species with potential for commercialization, there is a need to develop fruit-based allometric equations for estimating wild fruit biomass production by the species.

3.2. Research questions and hypothesis

The investigations carried out in the current study were based on the following research questions:

(1) Are tree parameters of *S. madagascariensis*, *S. spinosa,* and *T. emetica* allometrically correlated with their respective fruit biomass?
(2) Which among the tree parameters is the most relevant in predicting the fruit biomass of *S. madagascariensis*, *S. spinosa,* and *T. emetica*?
(3) How is biomass allocated in the fruit components of *S. madagascariensis*, *S. spinosa,* and *T. emetica*?
(4) What is the fruit biomass production potential of savannah woodlands in KwaZulu-Natal?

This study presumes that tree parameters of *S. madagascariensis*, *S. spinosa,* and *T. emetica* are strongly correlated with their fruit biomass and that correlation can be described by allometric equations. In addition, the amount of fruit juice, fruit puree, fruit pulp, or oil can be derived from the fruit biomass using regressions. This study also assumes that the fruit biomass production in savannah woodlands can sustain large-scale ventures of commercial harvesting of the fruits from the wild.

3.3. Aim and objectives of the study

This study aims to develop allometric equations for estimating and predicting the biomass of *S. madagascariensis*, *S. spinosa,* and *T. emetica* fruits and the amount of products that can be obtained from the fruits in the northern coastal regions of KwaZulu-Natal.

Specific objectives of this study are:

(1) To develop fruit-based allometric equations for *Strychnos madagascariensis* and *S. spinosa*;
(2) To determine biomass allocation between fruit components of *Strychnos madagascariensis* and *Strychnos spinosa* and to derive the carbon (C) stocks sequestrated by fruits;
(3) To evaluate the production potential of the Central Portions of the Umhlabuyalingana Municipality (CPUM) in terms of fruit biomass of *Strychnos madagascariensis* and *S. spinosa*;
(4) To develop allometric equations that predict the amount of fruits and the biomass of seeds of *T. emetica.*

CHAPTER 4: FRUIT ALLOMETRY OF *S. MADAGASCARIENSIS* AND *S. SPINOSA*

4.1. Full title

Fruit-based allometry of *Strychnos madagascariensis* and *S. spinosa* (Loganiaceae) in the savannah woodlands of the Umhlabuyalingana municipality, KwaZulu-Natal, South Africa.

4.2. Abstract

Savannah woodlands of South Africa are dominated by fruit tree species that have a potential for commercial harvest from the wild. Among them are *S. madagascariensis* and *S. spinosa.* However, allometric equations that enable the quantification of fruit biomass of trees are non-existent. The aim of the study being reported in this chapter was to develop fruit-based allometric equations for *S. madagascariensis* and *S. spinosa* species. A total of 80 trees were selected by applying a stratified sampling approach according to four stem diameter classes during fruit ripening period. For each tree, the following parameters were measured: fruit biomass, diameter at breast height (DBH), canopy diameter, and total height. Six forms of the allometric models were fitted to the data using ordinary least squares method. The Akaike information criterion was used to select the best models and the Root Mean Squared Error (RMSE) was used to evaluate the quality of the predictions. DBH was the only appropriate variable in the prediction of the fruit biomass and explained 99.9% of the variation in fruit biomass. The simple linear regressions linking the DBH (in cm) to the total fresh fruit biomass (FB; in kg) were the best models and were expressed by (1) $FB = 1.0243 \times DBH^{1.1841}$; and (2) $FB = 1.0297 \times DBH^{1.1956}$; respectively for *Strychnos madagascariensis* and *Strychnos spinosa.* These equations provided realistic predictions of fresh fruit biomass. They induced on average a prediction error of 5.4 kg on the total fresh fruit biomass of a tree. Larger trees (DBH > 25 cm for *S. madagascariensis*; DBH > 11 cm for *S. spinosa*) were more susceptible to fruit biomass prediction errors than smaller trees. This study showed that simple linear regression basing on DBH is the best approach to estimate fresh fruit biomass of trees in savannah woodlands.

Keywords: allometric equation; fruit biomass; prediction error.

4.3. Introduction

The vegetation of South Africa has a high diversity of plant species (Vlok and Euston-Brown 2002; Vlok et al. 2003; Mucina and Rutherford 2006). In particular, the sandy forests of the Pondoland in KwaZulu-Natal province have the highest diversity of fruit-bearing species (McKenzie 1988; Boon 2010; Mucina 2018), a potential primary source of income and vitamin C for the local community (Nkosi et al. 2020). The fruits include the wild plum (*Harpephyllum caffrum*), the mobola plum (*Parinari curatellifolia*), the wild medlar (*Vangueria infausta*), the natal apricot (*Dovyalis longispina*), the marula (*Sclerocarya birrea*), the green monkey orange (*Strychnos spinosa*), the black monkey orange (*Strychnos madagascariensis*), the large sour plum (*Ximenia caffra*), *Salacia krausii*, and many others. Many of these fruit trees, such as *S. birrea*, *S. madagascariensis*, *S. spinosa,* and suffrutices such as *S. krausii* and *P. curatellifolia* exist in great abundance with potential for commercial harvesting from the wild, which can boost rural employment and household economies (Nkosi et al. 2020). For example, the processing of indigenous fruits into juices and jams can generate additional revenues (Ngadze et al. 2017). Indigenous edible wild fruits can enhance food security (Koffi et al. 2020). In addition to the edible fruit pulp products, there exist in abundance some indigenous plants whose seeds or fruits contain oil which can also be commercially harvested from the wild. These include *Trichilia emetica*, *X. caffra*, *S. birrea*, *S. madagascariensis*, among others. To assess the potential for commercial exploitation of these plants from the wild, the quantification of the seasonal fruit biomass production is of paramount importance, and the use of fruit-based allometric models is invaluable in this assessment.

Allometry is a study of the correlation between measurable components/characteristics of an object and its overall structure (Gould 1966; Reitz et al. 1987; Gayon 2000). It is a concept applied in several scientific disciplines (Archibald and Bond 2003; Bohlman and O'Brien 2006; Dietze et al. 2008; Jackson et al. 2018). In forestry, allometry is used to quantify and predict the biomass of a tree or a compartment of a tree from parameters such as stem diameter (Maniatis et al. 2011; Fayolle et al. 2013a), height (Alemdag 1981; Ebuy et al. 2011; Mensah et al. 2017; Mensah et al. 2018), and wood specific density (Brown et al. 1989; Chave et al. 2005). The choice of the specific tree compartment whose biomass is to be estimated depends on the outcome desired and the forest type involved (Fortier et al. 2017). Thus, there are different types of allometric equations. Currently, there are pantropical allometric equations for estimating the total above-ground biomass of moist tropical forests (Brown and Lugo 1992; Chave et al. 2001) usually with the intention of assessing the contribution of the forest ecosystems to carbon dioxide reduction (Brown and Lugo 1982; Chambers et al. 2001; Pearson and Brown 2005). For logging operations and associated management of tropical forests, allometric equations are developed to estimate the marketable portion of the stem (Fayolle et al. 2013b). In open woodland forests (White 1983), allometric equations are developed for several reasons. In addition to the quantification of carbon sequestration by trees and shrubs (Ryan et al. 2011), the development of allometric equations is also oriented towards the study of the vegetative structure of trees (Murray 1927; Mensah et al. 2016). But as roots, branches, foliage, and fruits biomass represent a major part of the total tree biomass in savannah woodlands and open forests (Frost et al. 1986; Campbell et al. 1996; Poorter et al. 2011), allometric equations are also developed according to tree compartments. Thus, there exist above-ground and below-ground allometric equations (Kuyah et al. 2012a; Kuyah et al. 2012b), stem-based allometric equations (Fortier et al. 2017), branch-based allometric equations (Kaitaniemi et al. 2020), foliage-based allometric equations (Lehtonen 2005; Socha and Wezyk 2007), and fruit-based allometric equations (Peters et al. 1988). Fruit-based allometry was pioneered by Peters et al. (1988) by developing an allometric equation linking the stem diameter to the fruit biomass of trees and shrubs. No further studies have since been reported for the fruit-based allometry, probably because the need to quantify fruit biomass in the wild was not yet pressing.

Actually, in the district of UMkhanyakude, located in the northern coastal region of the KwaZulu-Natal province in South Africa, the need to quantify fruit biomass production of indigenous fruit tree species from the wild is growing. The UMkhanyakude district is endowed with a high density of *S. madagascariensis* and *S. spinosa* trees, edible indigenous fruit plants. These plants are adapted to harsh environmental conditions such as poor soil fertility and dry climates (Ngemakwe et al. 2017). They play a fundamental role in the development of rural economies and poverty alleviation in the district (Nkosi et al. 2020). *S. madagascariensis* trees produce edible fruits. Though not highly palatable, the processing of its seed coat into a kind of food by locals yields high amounts of oil. The fruits and the powdered bark produce a useful tonic. A paste that is made from the fruit is processed into dried products that are used in the treatment of immune-compromised people (Ngadze et al. 2017). *S. spinosa* trees produce highly appreciated edible fruits that are rich in macronutrients and dietary phytochemicals (Boon 2010; Ngemakwe et al. 2017). Depending on the extraction methods used, the fruits generate sweet juice, pulps, purees, and nectars. *S. spinosa* is ranked as the first most important indigenous fruit tree species in the province of KwaZulu-Natal (Nkosi et al. 2020). Traditional production of fruit juice from *S. spinosa* species and the use of improved technologies could potentially benefit cooperatives and small-scale processors by expanding what they sell and therefore increase their incomes (Ngadze et al. 2017; Ngemakwe et al. 2017). The marketing of *S. madagascariensis* and *S. spinosa* fruits, as well as their by-products, could contribute towards economic growth in UMkhanyakude district (Nkosi et al. 2020).

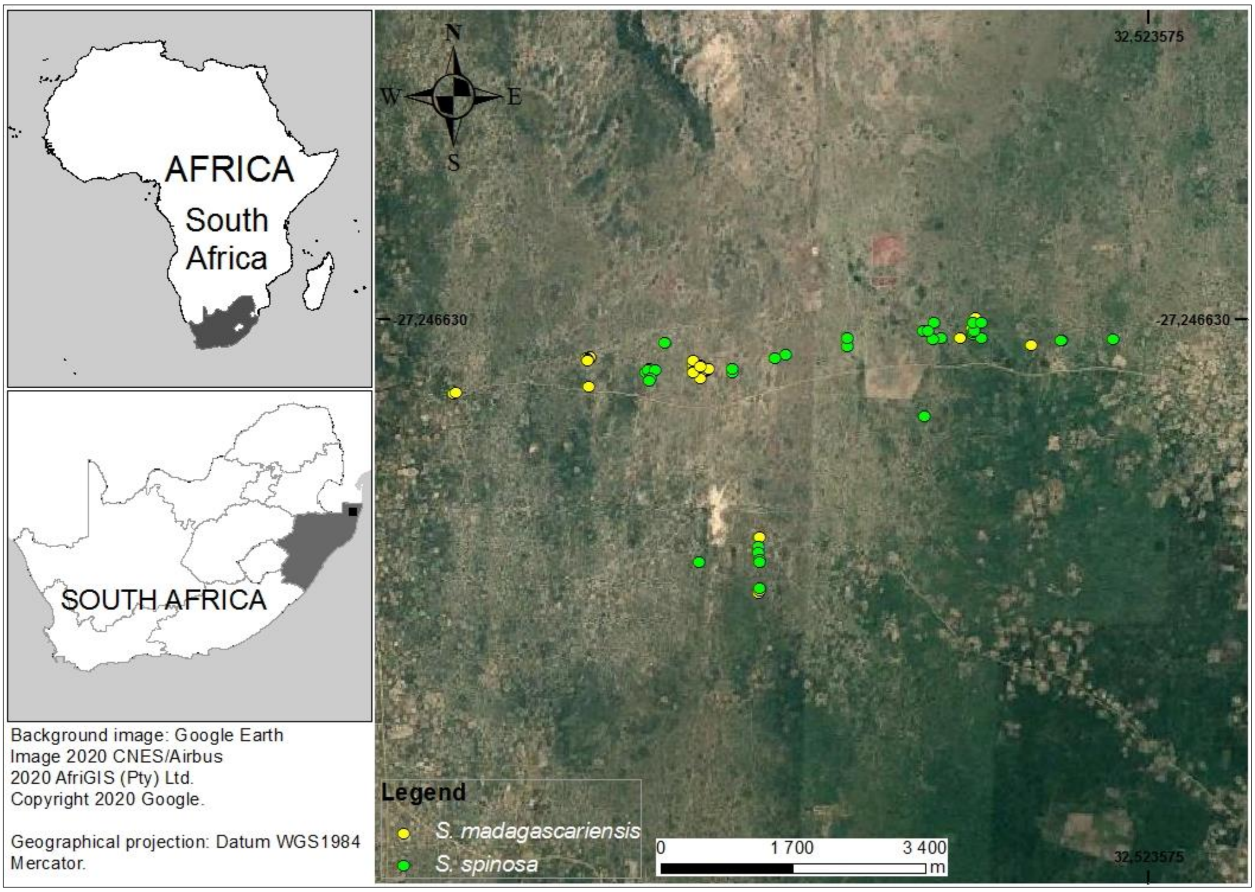
However, thus far, there has been no case of agro-industrial and agribusiness development involving *S. madagascariensis* and *S. spinosa* fruits. This is because of the lack of the implementation of a profitable business model. This depends on an accurate assessment of fruit biomass production from the wild. Therefore, fruit-based allometric equations of *S. madagascariensis* and *S. spinosa* remain indispensable tools in this assessment. The study reported in this chapter aims to calibrate allometric equations for the quantification and the prediction of the fruit biomass of *S. madagascariensis* and *S. spinosa* species in the Umhlabuyalingana municipality, KwaZulu-Natal, South Africa.

4.4. Materials and methods

4.4.1. Study area and species description

This study was conducted in the municipality of Umhlabuyalingana, located in the district of UMkhanyakude. The district of UMkhanyakude is situated in the northern coastal region of the province of KwaZulu-Natal, in South Africa (Chap4-Figure 1). The vegetation type of the municipality is often described as Maputaland coastal thicket (Mucina 2018), but the land cover is dominated by savanna woodland formation (Jewitt 2018) with a humid coastal climate, normally frost-free. The maximum temperature reaches 35 °C while the minimum temperature in the coldest month (June) reaches 14 °C. The soils are sandy (Botha and Porat 2007; IDP 2017). *S. madagascariensis* (Poir.) and *S. spinosa* (Lam.) species are indigenous to tropical and subtropical Africa. They belong to the Loganiaceae family and they are known for their large fruits (Chap4-

Figure 2). *S. spinosa* is commonly called iHlala (isiZulu), Doringklapper (Afrikaans), and Kikwakwa (Kiswahili). *S. madagascariensis* is locally known as Umkwakwa (isiZulu).



Chap4-Figure 1: Location map of harvested trees of *Strychnos madagascariensis* (yellow dots) and *Strychnos spinosa* (green dots).

Chap4-Figure 2: Collection of fruits from the *Strychnos madagascariensis* (left) and *Strychnos spinosa* trees (right).

4.4.2. Tree sampling and measurements

The trees were selected in an area of 3804 ha by a stratified sampling approach according to the sizes of the diameter at breast height (DBH). The DBH sizes were categorized into four classes namely: (1) 2.0 to 7.9 cm; (2) 8.0 to 13.9 cm; (3) 14.0 to 19.9 cm; and (4) 20.0 to 35 cm. Eighty trees (40 trees per species) were selected for measurements. Each diameter class for each of the *Strychnos* species was represented by 10 trees. However, for *Strychnos spinosa*, the last diameter class (4) had six trees. Only trees with well developed and ripe fruits were selected and measured. Tree measurements included DBH, canopy diameter, and total height. The tree canopy[2] diameter was obtained from an average of two orthogonal diameters of the tree crown. Orthogonal diameters were measured after a ground-projection of crown perimeters following North-South and East-West directions. All the fruits of each sampled tree, including the fallen fruits, were counted. From each sampled tree, 20 non-fallen fruits were randomly collected for biomass measurements. For trees having less than 20

[2] Canopy volume was not involved in this study. Only canopy diameter was considered because *Strychnos* species have a terminal inflorescence and the fruits are generally borne in peripheral branches (Mwamba 2006).

fruits, only five fruits were collected. The collected fruits were individually weighed fresh. The individual fresh biomasses of the collected fruits from a tree were used to calculate the mean fruit biomass of that tree. The total fruit biomass of a tree was obtained using the calculated mean fruit biomass of that tree multiplied by its total number of fruits (Peters et al. 1988). The measured tree parameters were used as the predictors (Brown et al. 1989; Maniatis et al. 2011) of the total fruit biomass of the harvested trees (Peters et al. 1988).

In this study, the only stratum that was considered in tree selection is DBH category. This is because, in the study area, there was only one and unique vegetation type involved (savannah woodlands) whose physical and environmental attributes (soil type, rainfall, and temperature) are generally equal. The only factor that could create differentiation among trees is the DBH size category. This factor was therefore used to ensure the representativeness of selected trees according to DBH ranges. A stratified approach is always the best to cover strata of differentiation. In this case, DBH category was the only possible stratum of variations. For multi-stemmed trees, mostly met with *S. madagascariensis*, the DBH of each stem was measured and I have considered the mean value.

4.4.3. Statistical analysis

The coefficient of correlation and graphic exploration were used to identify the forms of the allometric models that were likely to describe the collected data. Six forms of the log-transformed linear models were fitted to the data (Chap4-Table 1). Both simple and multiple regression models were tested. The fitting of the allometric models of both *Strychnos* species was done using the ordinary least squares method (OLS; Picard et al. 2012). The attributes of the models were assessed using the coefficient of determination (R^2) and the residual standard error (RSE). Akaike information criterion (AIC) was used to select the best-fit models (Akaike 1974). A correction factor (CF) was applied to the selected models to correct the systematic bias induced by the logarithmic transformation (Duan 1983; Chave et al. 2014).

Chap4-Table 1: Allometric models linking the fresh fruit biomass (*FB*, in kg) to the diameter at breast height (*DBH*, in cm), to the tree canopy diameter (*Dc*, in cm), and to the tree height (*H*, in m) by a Natural logarithmic function (ln) where a_0, a_1, and a_2 are the coefficients to be estimated and ε the residual error.

Model	Expression
Simple regression	
Model 1	$\ln(FB) = a_0 + a_1 \ln(DBH) + \varepsilon$
Model 2	$\ln(FB) = a_0 + a_1 \ln(Dc) + \varepsilon$
Model 3	$\ln(FB) = a_0 + a_1 \ln(H) + \varepsilon$
Multiple regression	
Model 4	$\ln(FB) = a_0 + a_1 \ln(DBH) + a_2 \ln(H) + \varepsilon$
Model 5	$\ln(FB) = a_0 + a_1 \ln(Dc) + a_2 \ln(H) + \varepsilon$
Model 6	$\ln(FB) = a_0 + a_1 \ln(DBH) + a_2 \ln(Dc) + \varepsilon$

Root Mean Squared Error (RMSE) was used to evaluate the quality of the predictions (Brown et al. 1989). The RMSE (Chap4-Equation 1), the CF (Chap4-Equation 2), and the AIC (Chap4-Equation 3) were obtained using the following expressions:

$$\mathrm{RMSE}= \sqrt{\frac{\sum_{i=1}^{n}\left(B_{est,\ i} - B_{obs,\ i}\right)^2}{n}} \qquad \text{(Chap4-Equation 1)}$$

$$\mathrm{CF}= (RSE^2) / 2 \qquad \text{(Chap4-Equation 2)}$$

$$\mathrm{AIC}= -2 \ln(L) + 2q \qquad \text{(Chap4-Equation 3)}$$

Where n represents the sample size per species, $B_{est,\ i}$ and $B_{obs,\ i}$ respectively represent the estimated and the measured fruit biomass for a given tree i (in kg; Chap4-Equation 1). *RSE* is the residual standard error (Chap4-Equation 2). The term L represents the likelihood of the fitted model and the term q denotes the number of estimated free parameters of the models (Chap4-Equation 3; Picard et al. 2012). Prediction errors of the selected models were calculated by the difference between the predicted fruit biomass and the observed fruit biomass. A nonparametric regression between the prediction error and the DBH was fitted to present the deviations in the fruit biomass predictions. All the statistical analyses were carried out using the R-software (R DEVELOPMENT CORE TEAM 2014). The linear models and the nonparametric regression were fitted to the data using the *lm* and the *lowess* functions, respectively.

4.5. Results

4.5.1. Dendrometric variables and fruit biomass

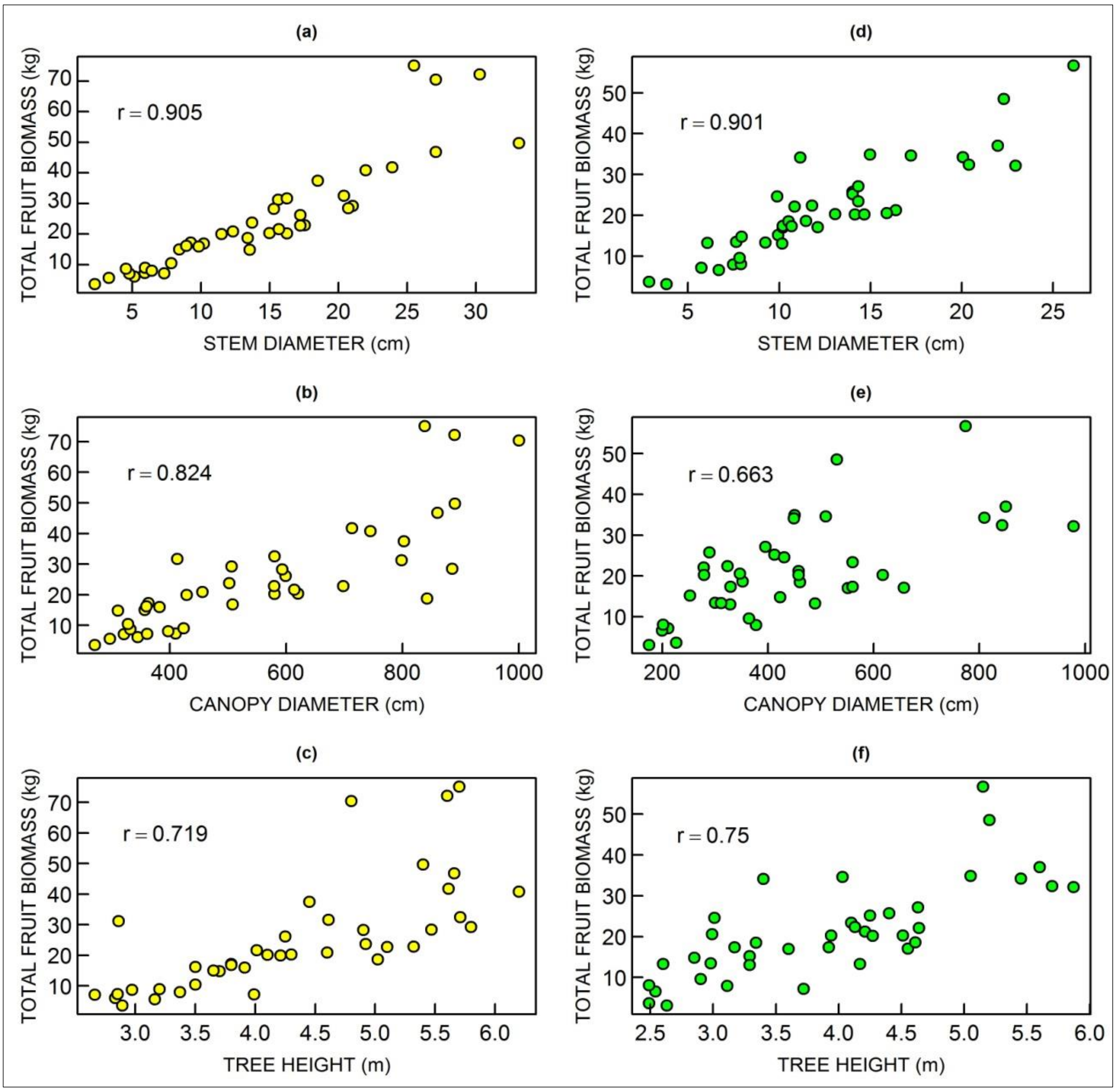
There were wide variations in stem diameter, tree height, canopy diameter, and fruit biomass of the two species among the trees that were measured (Chap4-Table 2). The DBH of the *S. madagascariensis* species varied between 2.26 cm and 33.12 cm while the DBH of the *S. spinosa* species extended between 2.87 cm and 26.11 cm. The maximum height of the *S. madagascariensis* and *S. spinosa* trees were 6.20 and 5.87 m, respectively. The total fresh fruit biomass per tree of *S. madagascariensis* varied between 3.63 and 75.13 kg while that of *S. spinosa* species varied between 3.12 and 56.75 kg. The number of fruits per tree for *S. madagascariensis* ranged from 7 to 259 and in *S. spinosa* species the number ranged from 6 to 128.

Chap4-Table 2: Summary of statistical dispersion parameters of measured variables per species. The standard deviation (SD) is given for the mean values.

Variables		Dispersion parameters			
		Minimum	Median	Mean±SD	Maximum
Strychnos madagascariensis					
Fruit total biomass	(kg)	3.63	20.64	25.08±17.9	75.13
Diameter at breast height	(cm)	2.26	14.33	14.49± 7.7	33.12
Canopy diameter	(cm)	271.0	507.0	554.9± 209.1	1000.00
Tree height	(m)	2.66	4.23	4.31 ± 1.01	6.20
Number of fruits		7	54	67± 51.6	259
Strychnos spinosa					
Fruit total biomass	(kg)	3.12	20.24	21.34±11.5	56.75
Diameter at breast height	(cm)	2.87	11.30	12.47± 5.3	26.11
Canopy diameter	(cm)	175.0	417.5	445.1±196.1	978.00
Tree height	(m)	2.49	3.98	3.92± 0.9	5.87
Number of fruits		6	47	50 ± 28.7	128

4.5.2. Correlations and graphic exploration

The highest values of the coefficient of correlation (r) were observed in the relationship between the total fruit biomass and the DBH for both *S. madagascariensis* (r = 0.905) and *S. spinosa* species (r = 0.901). DBH had a linear relationship with the fruit biomass (Chap4-Figure 3: graph *a* and *d*). Canopy diameter was less positively correlated with the fruit biomass (r = 0.824 for *S. madagascariensis*; r = 0.663 for *S. spinosa*) compared to the DBH. The correlation coefficients between tree height and fruit biomass of the *S. madagascariensis* and *S. spinosa* species were 0.719 and 0.750, respectively. The variability in fruit biomass was large for canopy diameter and tree height in both species, but linear nature of the relationships was evident (Chap4-Figure 3: graph *b*, *c*, *e*, and *f*).



Chap4-Figure 3: Graphic exploration and coefficients of correlation (r) between the fruit biomass and the measured dendrometric variables of *Strychnos madagascariensis* (yellow dots) and *Strychnos spinosa* (green dots).

4.5.3. Fitted fruit-based allometric equations

Among the models that were fitted to the data for predicting the fruit biomass from the DBH, canopy diameter, and stem diameter, Models 1b, 2 and 5 were concurrent as they all had coefficients that were statistically significant (Chap4-Table 3). Between these three models, Model 1b had the highest value of coefficient of determination (R^2= 0.99 for both species) and the lowest values of the Akaike information criteria (AIC= -4.91 for

S. madagascariensis; AIC= 3.02 for *S. spinosa*). Model 1b was the best model for both species. This model was generated from Model 1 because the ordinate at the origin (a_0) of Model 1 was statistically insignificant.

Chap4-Table 3: The fitting of the coefficients "a_0, a_1, a_2" of the allometric models with their significance codes reported at the confidence interval of 99.9% (***), 99 % (**), 95% (*), 90% (.), and 0% (). The coefficient of determination (R^2), the residual standard error (RSE) and the Akaike information criteria (AIC) are given for each model. The best models are hatched in orange.

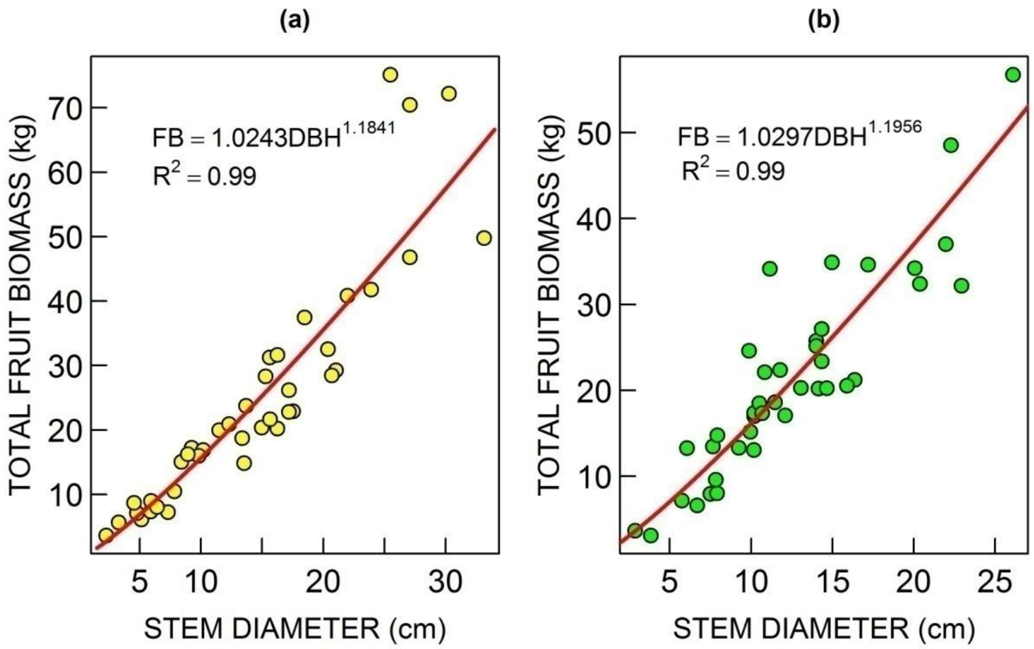
Model	Coefficients and significance codes			R^2	RSE	AIC
	a_0	a_1	a_2			
Strychnos madagascariensis						
Model 1	0.2042	1.1074 ***		0.91	0.216	-5.07
Model 1b		1.1841 ***		0.99	0.219	-4.91
Model 2	-7.3854 ***	1.6581 ***		0.71	0.390	42.24
Model 3	-0.5555	2.4658 ***		0.65	0.430	50.06
Model 4	0.2265	1.1193 ***	-0.0364	0.91	0.219	-3.08
Model 5	-5.5167 ***	1.0678 ***	1.2709 ***	0.79	0.329	29.51
Model 6	-0.9847	0.9861 ***	0.2389	0.91	0.213	-5.03
Strychnos spinosa						
Model 1	-0.1089	1.2389 ***		0.85	0.244	4.72
Model 1b		1.1956 ***		0.99	0.242	3.022
Model 2	-3.5614 ***	1.0745 ***		0.53	0.438	51.45
Model 3	0.3137	1.9323 ***		0.57	0.411	46.42
Model 4	-0.1991	1.1245 ***	0.2752	0.85	0.243	5.44
Model 5	-1.9980 *	0.5335 *	1.2632 **	0.62	0.385	42.09
Model 6	-0.7366	1.1423 ***	0.1434	0.85	0.244	5.539

The conversion from the logarithmic form of the fitted Model 1b to the exponential form and the application of the correction factors produced Chap4-Equation 4 for *S. madagascariensis* and Chap4-Equation 5 for *S. spinosa* with improved goodness of fit (Chap4-Figure 4), and therefore more accurate prediction of fruit biomass basing on stem diameter.

$FB = 1.0243 \times DBH^{1.1841}$ (Chap4-Equation 4)

$FB = 1.0297 \times DBH^{1.1956}$ (Chap4-Equation 5)

Where FB is the total fresh fruit biomass of a tree (in kg) and *DBH* is the diameter at breast height of a tree (in cm).



Chap4-Figure 4: Prediction curves of the fruit biomass (FB) of *Strychnos madagascariensis* (a) and *Strychnos spinosa* (b) by the fitted allometric equations based on the diameter at breast height (DBH). The coefficients of determination (R^2) are given.

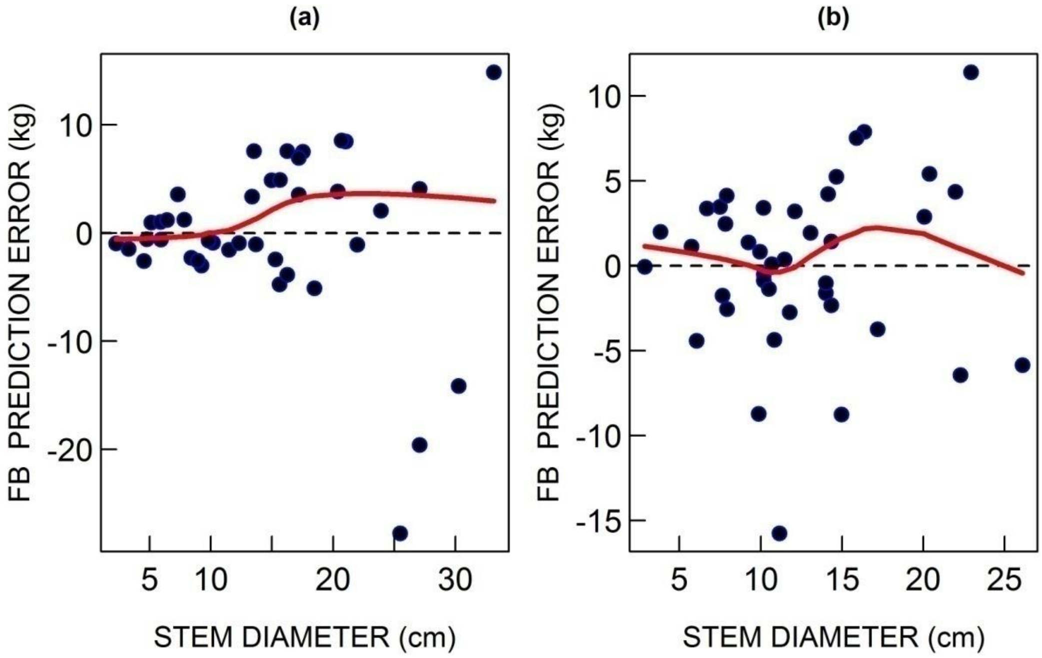
Step-wise regression was also used in the fitting of fruit-based equations of this chapter. This was conducted with 21 further models which were not mentioned in the methodology. However, this has led to the same results (Chap4-Equation 4 and Chap4-Equation 5). Simple regression model based on DBH alone was the most relevant model. The fitting of the 21 models is detailed in the script file which is published in *Trees, Forest and People* under "supplementary material". The title of the file is "*R Codes_used_for_Data analysis*" and the analysis is in the section "*FITTING OF MODELS*" (This can be found at https://ars.els-cdn.com/content/image/1-s2.0-S266671932030025X-mmc1.txt).

4.5.4. Evaluation of the equations

The average error associated with Chap4-Equation 4 for predicting the total fruit biomass of *S. madagascariensis* from a single tree was 5.9 kg whereas that for Chap4-Equation 5 for predicting *S. spinosa* total fruit biomass of a single tree was 5.0 kg (Chap4-Table 4). The absolute estimation error of the fruit biomass for the *S. madagascariensis* equation was higher than 10 kg for trees larger than 25 cm of DBH. For the *S. spinosa* equation, the absolute estimation error of the fruit biomass was higher for the trees larger than 11 cm of DBH (Chap4-Figure 5).

Chap4-Table 4: The root mean square error (RMSE) of the predicted fruit biomass by the fitted equations per diameter at breast height (DBH) class and per species.

DBH class (cm)	RMSE (kg)	RMSE (kg)
	S. madagascariensis	*S. spinosa*
[2, 7.9]	1.7	2.8
[8, 13.9]	3.1	5.2
[14, 19.9]	5.4	5.3
[20, 35]	13.3	6.7
Mean	5.9	5.0



Chap4-Figure 5: Prediction errors of the fruit biomass (FB) by the fitted allometric equations of *Strychnos madagascariensis* (a) and *Strychnos spinosa* (b) according to the stem diameter. The zero values (on dotted black line) indicate a perfect match between the predicted and the measured fruit biomass. The positive and the negative values denote the over and the under-estimation of the fruit biomass, respectively.

4.6. Discussion

4.6.1. Correlations and graphic exploration

Currently, a major obstacle in estimating the amount of fruit biomass production of indigenous fruit plants is the lack of reliable regression equations which can convert accurately the parameters measured directly in the field into biomass. In the current study, correlation tests between the total fruit biomass per tree and the DBH showed that the DBH was highly correlated to the total fruit biomass for both *S*. *madagascariensis* (r = 0.905; Chap4-Figure 3, graph *a*) and *S. spinosa* species (r = 0.901; Chap4-Figure 3, graph *d*). Surprisingly, the correlation between the canopy diameter and the total fruit biomass was lower than that of the DBH for both *Strychnos* species (Chap4-Figure 3, graph *b* and *e*). Because fruits are borne on the branches, and their number is therefore supposed to depend on flowering points of the branches, it was reasonable to expect that there should be a higher correlation between fruit biomass and the canopy diameter than with stem diameter, but this was not the case. In *S*. *madagascariensis*, the coefficient of correlation for the relationship between the canopy diameter and the fruit biomass was 0.824, which was lower than that for the relationship between stem diameter and fruit biomass. Thus, the fruit production of *S*. *madagascariensis* was not as strongly influenced by the canopy diameter as it was by the DBH. A similar outcome was obtained for *S*. *spinosa*, and more surprisingly the coefficient of correlation between the canopy diameter and the fruit biomass for the *S*. *spinosa* was the lowest (r = 0.663; Chap4-Figure 3, graph *e*), and markedly lower than the correlation between tree height and fruit biomass. The relationship between canopy diameter and the fruit biomass for *S*. *spinosa* was substantially weaker than in the case for *S*. *madagascariensis* despite that both species flower and fruit at the same time. Furthermore, they grow in association. The weak relationship between the fruit biomass and the canopy diameter in *S*. *spinosa* emanated from marked variability in fruit biomass production. The same outcome is also reported for *S. birrea* (Nyoka et al. 2015). However, the reasons for the high variability could not be determined from the nature of the research, but factors such as water deficit and mineral nutrient deficiencies cannot be ruled out as the season in which the fruits were produced was droughty. If these factors were responsible for high variability in fruit biomass per tree, the results therefore infer that *S*. *madagascariensis* is more tolerant to these factors than *S*. *spinosa*. It is therefore herein suggested that another set of measurements be taken when fruit production has occurred in a wetter season.

4.6.2. Fitted fruit-based allometric equations

Based on the results obtained, DBH was the most important parameter in the prediction of the fruit biomass. These findings corroborate with the available fruit-based equation of Peters et al. (1988) wherein DBH was used as the main predictor of the fruit biomass. In addition, Peters et al. (1988)'s fruit-based equation had no ordinate at the origin. The results of this study confirm that the ordinate at the origin is not relevant for the fruit biomass regression. This can practically be explained by the fact that fruit trees can only start bearing fruits after they have reached a certain DBH size or age (Nyoka et al. 2015).

Several scientists have demonstrated the relevance of the DBH in the biomass estimations (Djomo et al. 2010; Maniatis et al. 2011; Fayolle et al. 2013a). Most of the existing allometric equations involve the DBH as a main predictor (Alemdag 1981; Chave et al. 2004; Chidumayo 2013). In the moist tropical forests, the tree height and the wood specific density are additional relevant parameters for the total above-ground biomass estimations (Brown et al. 1989; Chave et al. 2005; Ebuy et al. 2011). However, biomass prediction of larger trees is commonly subject to bias. This is common with DBH-based allometry. Larger trees are generally old and can therefore present significant differences in biomass production (not only fruit biomass). It remains to be tested whether the wood specific density or the age is a relevant parameter for the fruit biomass estimations of larger trees in the savannah woodlands.

4.6.3. Evaluation of the fitted fruit-based equations

Evaluation of the fitted equations for *S. madagascariensis* and *S. spinosa* showed that the average error that these equations can cause on the predictions of the fruit biomass of a single tree is 5.9 kg and 5.0 kg, respectively (Chap4-Table 4). These values seem to be large and risky because the small trees, having few fruits, can be liable to biased fruit biomass estimations. The values of the average prediction error obtained per diameter (DBH) class (Chap4-Table 4) enable a comprehensive evaluation of the prediction errors. The average errors associated with the fitted *S. madagascariensis* equation for the fruit biomass of a single tree are: 1.7 kg, 3.1 kg, 5.4 kg, and 13.3 kg, while the average errors for the fitted *S. spinosa* equation are 2.8 kg, 5.2 kg, 5.3 kg, and 6.7 kg, respectively from the lowest to the highest DBH class. In Chap4-Figure 4, it can be observed that the prediction curve is fitting to the point clouds in the manner that minimizes the deviations. In Chap4-Figure 5, the absolute deviations in fruit biomass predictions are concentrated around 5 kg. An analysis of the prediction errors in each diameter class leads to the conclusion that the fitted allometric equations of both *Strychnos* species are realistic in the fruit biomass prediction. However, these fitted equations have to be tested with data that were not used to calibrate them. In allometry, it is advised to collect two groups of data, one for the calibration of equations and the other one for the testing of the calibrated equations to assess the possible deviations in the estimation of the biomass. The deviations in biomass estimations are common (Molto et al. 2012; Vieilledent et al. 2012; Chave et al. 2014; Ngomanda et al. 2014). This study did not collect the additional (neutral) data to assess the deviations in the fruit biomass predictions. Thus, the domain of validity of the fitted fruit-based equations in this study has to be considered before their use. A total of 80 trees, with 20 trees for each DBH class, were considered representative of the whole vegetation and covered all possible tree sizes. This makes the fiited equations reliable for the study area. However, further studies are necessary to determine the risk associated with the extension of the area of application of these equations. Contributions towards validating these equations within and outside the scope of this study will be essential in the estimations of fruit biomass.

4.7. Conclusion

This study developed allometric equations for estimating fresh fruit biomass of *S. madagascariensis* and *S. spinosa* in the savannah woodlands of the Umhlabuyalingana municipality, in the province of KwaZulu-Natal, South Africa. These allometric equations were developed from the data collected on 80 trees whose DBH covered a range of 2.26 cm to 33.12 cm. It was proven that DBH is the most important parameter in fruit biomass estimations. In contrast, the canopy diameter and the height of trees did not improve the goodness of fit of fruit-based allometric equations despite their positive correlations with the fruit biomass. It remains to be tested if other parameters such as wood specific density and age would explain the variations in fruit biomass of trees. The first evaluations of the fitted fruit-based allometric equations showed that the average errors that these equations are likely to induce on the predictions of the fruit biomass of a single tree are minor when considered per DBH class. Even if validation studies are yet to be done, the fruit-based allometric equations developed in this study are the only available tools for the quantification and prediction of the fresh fruit biomass of the *S. madagascariensis* and *S. spinosa* species.

CHAPTER 5: BIOMASS AND CARBON STOCKS IN *STRYCHNOS* FRUITS

5.1. Full title

Deriving biomass allocation and carbon stocks in fruit components of *Strychnos madagascariensis* (Poir.) and *Strychnos spinosa* (Lam.) in South Africa.

5.2. Abstract

Fruits contribute to carbon (C) fixation in fruit tree species of savannah woodlands despite that the C fixed in fruits is rapidly turned back to carbon dioxide (CO_2) when the fruits decompose or are eaten. The aim of the study reported in this chapter was to determine biomass allocation between fruit components of *Strychnos madagascariensis* and *Strychnos spinosa* and to derive the C stocks sequestrated by fruits. A total of 400 ripe fruits were harvested from trees distributed in seven plots across the UMkhanyakude district. Fruit shell and pulp were separated from seeds. Puree and juice of *S. spinosa* were separated by centrifugation and steam extraction, respectively. Moisture contents of the fruit components were measured. For *S. madagascariensis* fruits, seeds contributed the most biomass (50.2 %), followed by the shell (30.8 %), and pulp had the least biomass (16.7 %). The loss of material was 2.3 %. For *S. spinosa*, the largest part of fruit biomass was in the shell (41.8 %), followed by puree (25.6 %), seeds (18.6 %), juice (6.2 %), and pulp (0.9 %). The loss of material was 6.9 %. Fruit dry biomass (FDB; in g) and fruit carbon stocks (CB; in g) were both related to fruit diameter (D; in cm) for *S. madagascariensis* ($FDB = 1.022 \times D^{2.492}$; $CB = 0.463 \times D^{2.539}$) and *S. spinosa* ($FDB = 1.015 \times D^{2.38}$; $CB = 0.198 \times D^{2.821}$). Proportion values and regression techniques were both valid methods to derive biomass and carbon stocks of the fruit and its components.

Keywords: fruit allometry; proportions; moisture content; carbon balance; savannah woodlands.

5.3. Introduction

Fruit trees play a very important role in the dynamics of carbon (C) in savannah woodlands (Wu et al. 2012). Because of their considerable annual production of fruit biomass, which can reach 510 kg ha^{-1} (Campbell et al. 1996), they are major sinks of C fixation in fruit tree species (Pérez-Piqueres et al. 2020). The CO_2 fixed by a mature fruit tree is also distributed to fruits (Sofo et al. 2005). Fruiting trees accumulate more C than non-fruiting trees (Wibbe et al. 1993) because of the high photosynthetic activity during the fruit cell division and expansion. Fruit trees play an important role in the global carbon sequestration (Pérez-Piqueres et al. 2020) despite that some trees with climacteric fruits can produce much ethylene and CO_2 gas during fruit ripening (Rodrigues et al. 2018). In addition to this ecosystem service, fruit trees contribute to food security (Koffi et al. 2020), employment, and income generation (Sulieman and Mariod 2019). In sub-tropical Africa, fruits are among the main sources of protein, energy, fibres, and minerals (Rodrigues et al. 2018). Fruit tree species belonging to the genus *Strychnos* are among the most appreciated in rural communities (Nkosi et al. 2020). The species prevalent in Africa include *Strychnos spinosa*, *S. madagascariensis*, *S. cocculoides*, *S. lucens, S. minfiensis, S. mitis*, *S. pungens*, *S. innocua*, *S. potatorum*, S. *icaja*, among others (Delaude et al. 1992). They are commonly called "Monkey Orange" in English (Salmona et al. 2015; Ngadze et al. 2019). They have greatly contributed to the development of traditional medicine (Beaufay et al. 2018; Razzaq et al. 2020) and pharmacology (Mors et al. 2000) thanks to their numerous alkaloids (Arunkumar et al. 2019; Saya et al. 2019; Gautam et al. 2020; He et al. 2020; Semenov et al. 2020).

In South Africa, the district of UMkhanyakude, located in the province of KwaZulu-Natal, is mainly dominated by two species of *Strychnos*, namely *S. spinosa* and *S. madagascariensis* (Boon 2010). These species are small trees that are indigenous to tropical and subtropical Africa (Sitrit et al. 2003). *Strychnos spinosa* can grow up to seven meters in height. It bears edible round-shaped fruits that resemble an orange. The fruit has an edible, juicy, and sweet pulp. It also contains many brown seeds (Rodrigues et al. 2018). The fruit of *S. madagascariensis* is not highly palatable, but its powdered bark produces a useful tonic. *Strychnos spinosa* is locally called iHlala, Kikwakwa, and Doringklapper respectively in isiZulu, Kiswahili, and Afrikaans while *S. madagascariensis* is known as Umkwakwa in isiZulu. These two species are among the most important multipurpose fruit trees in rural communities of KwaZulu-Natal (Nkosi et al. 2020; van Rayne et al. 2020). *Strychnos spinosa* is used as food and medicine (Mizrahi et al. 2002; Ngemakwe et al. 2017; Avakoudjo et al. 2020). Leaf extracts have wound-healing activity (Hassan et al. 2020) and can treat infectious diseases (Isa et al. 2014). Extracts from unripe fruits are used as an antidote against snake bite venom (Mors et al. 2000). *Strychnos spinosa* has potential as an industrial crop for fruit juice based products (Rodrigues et al. 2018). On the other hand, *S. madagascariensis* fruit pulp and the seed testa have the potential for food product development (van Rayne et al. 2020). Although they may contain toxic alkaloids, the fruit pulp and seed testa are processed by some communities in Zimbabwe and South Africa into dried food products that provide nourishment during droughts and famine (Salmona et al. 2015; Ngadze et al. 2017; Shai et al. 2020; van Rayne et al. 2020). However, despite their large production of fruit biomass in the wild, which can reach more than 40 kg per tree (Ngemakwe et al. 2017), *S. spinosa* and *S. madagascariensis* are not yet widely commercialized and their fruits remain restricted to domestic consumption (Rodrigues et al. 2018).

Biomass is a term used to refer to the mass of living organisms, including plants, animals, and micro-organisms (Houghton 2008). In plants, biomass represents the dry weight of all organic matter (Focardi 2008) that can also be used as fuel (Basu 2018; Edomah 2018). Biomass is one of the most fundamental measurements in ecology (Chave et al. 2004; Steinman et al. 2017). It helps to evaluate the contribution of forest ecosystems in C sequestration (Chambers et al. 2001; Pearson and Brown 2005; Ryan et al. 2011). In savannah woodland trees, approximately 39 % of C stocks are sequestrated in the roots and 61 % in above-ground components (Chen et al. 2003; Dimobe et al. 2018). Biomass is distributed to various components namely the roots, the stem, the branches, the leaves, and the flowers or the fruits (Picard et al. 2012). The sum of the biomass of each compartment generates the total biomass of a tree (Henry et al. 2010; Mugasha et al. 2013). About 50 % of measured dry biomass represents the amount of C stored (Houghton, 2008; Jana et al. 2009; Paladinić et al. 2009; Chavan and Rasal 2011). There exist several methods for measuring the biomass of a tree or a component of a tree (Brown et al. 1989; Carreiras et al. 2013). Direct weighing is the most accurate method and allows the development of allometric equations which can subsequently be used to estimate biomass at a larger scale (Vieilledent et al. 2012).

Depending on the tree component whose biomass is estimated, there exist below-ground allometric equations (Kuyah et al. 2012b), stem-based equations (Fortier et al. 2017), branch-based equations (Kaitaniemi et al. 2020), foliage-based equations (Lehtonen 2005; Socha and Wezyk 2007), and fruit-based equations (Peters et al.1988; Akweni et al. 2020).

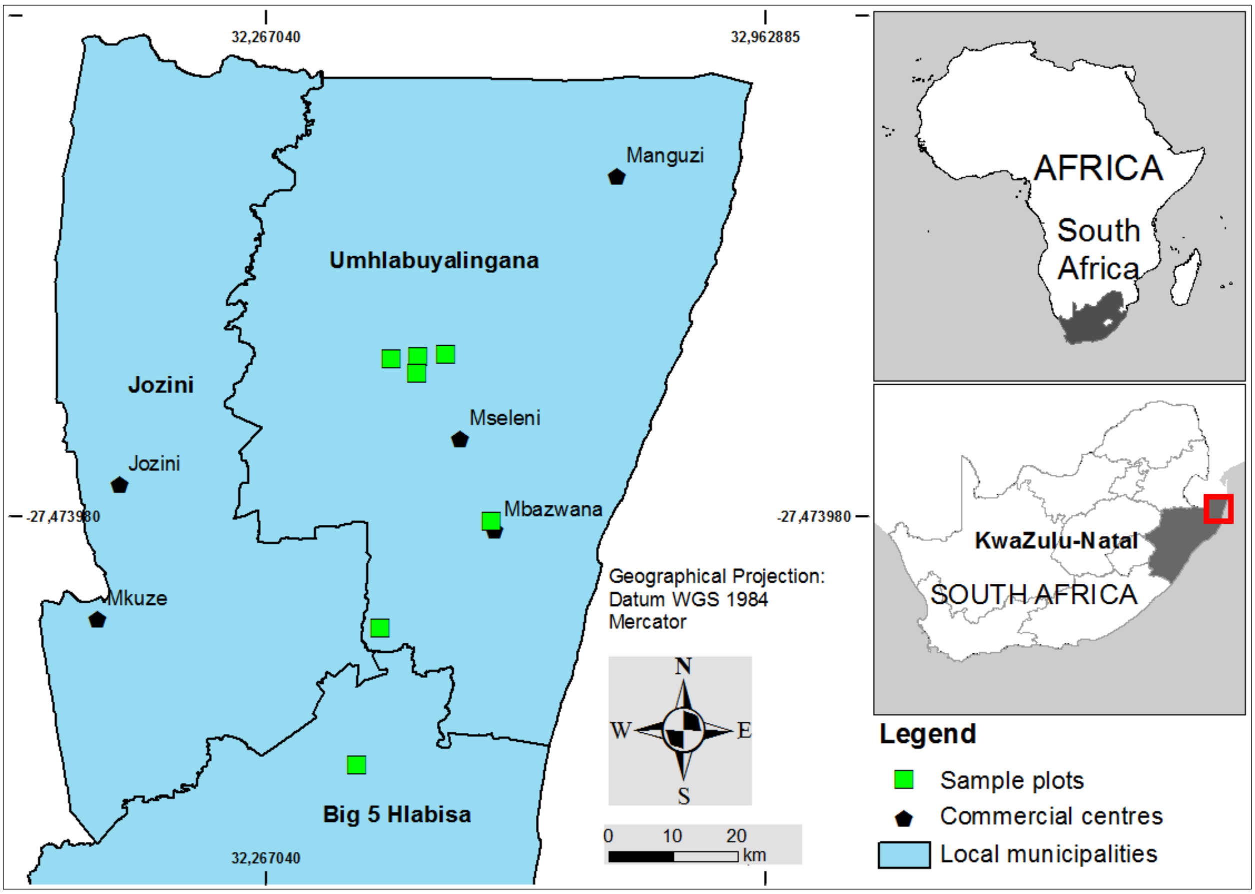
Currently, fruit-based allometric equations of *S. madagascariensis* and *S. spinosa* are available (Akweni et al. 2020). These equations enable the estimations of fruit biomass production from the wild. However, these fruit-based allometric equations were logically developed to estimate only the fresh fruit biomass, because in rural markets fruits are sold and eaten fresh (Rodrigues et al. 2018). Therefore, the estimation of dry fruit biomass and C sequestration by fruits are not yet possible at this stage for *S. madagascariensis* and *S. spinosa* species. In addition, parameters (moisture content and fruit density) that can help to convert fresh fruit biomass into dry biomass are not yet available for these species. Furthermore, their fruit components are different in composition and nature (Ngadze et al. 2017). The shell, pulp, and seeds are found in both fruits, but in addition to these components *S. spinosa* contains juice and puree. It is therefore ideal to investigate moisture content separately. This requires a good understanding of how fresh biomass is distributed between the components of the fruits. The study reported in this chapter aims to determine the partitioning of biomass between fruit components of *S. madagascariensis* and *S. spinosa* and to derive the C stocks sequestrated by fruits. The derivation of C stocks in fruits is an essential step towards the establishment of C balance in savannah woodlands. Because a large amount of C stocks fixed in fruits are rapidly released in the atmosphere as CO_2, CH_4, or C_2H_6 when the fruits are eaten. Marginally, fruits may contribute after decomposition processes to feeding the carbon stocks of the soils.

5.4. Materials and methods

5.4.1. Study area

This study was conducted in the UMkhanyakude district, located in the northern coastal region of KwaZulu-Natal province, in South Africa (Chap5-Figure 1). The district is largely covered by grassland and savannah vegetation (Jewitt 2018) which are part of the Maputaland coastal thicket biome (Mucina 2018). The soils of the area are sandy

(Botha and Porat 2007) and the climate is humid with temperatures ranging between 14 and 35°C.



Chap5-Figure 1: Location map of harvested plots in the UMkhanyakude district, KwaZulu-Natal province, South Africa.

5.4.2. Fruit sampling and biomass measurements

A total of 400 ripe fruits were harvested from seven square plots of 6400 m^2 each. The sample plots were identified according to the presence of *S. madagascariensis* and *S. spinosa* trees. In each plot, about 58 fruits (29 fruits per species) were collected from all trees found in the plot. From each tree, fruits were collected at random targeting only healthy mature (ripe) fruits still attached to the trees for *S. madagascariensis*. In the case of *S. spinosa*, ripe fruits were picked from the ground under the trees. In this species, fruits mostly attached to the trees are unripe. All the harvested fruits were brought to the laboratory where their fresh biomass and diameters were individually measured. The diameter of fruits was measured using diametric tape. After individual measurements, fruits were grouped into eight lots of 50 fruits each, that is to say, four lots for each species. Each lot was composed of 50 fruits to ensure representation of all possible sizes of mature fruits growing in the wild. For each fruit lot of *S. madagascariensis* (Chap5-Figure 2A), the shell of each fruit was broken and the pulp was separated from seeds (Chap5-Figure 2B) after which the shell, pulp, and seeds were weighed fresh (Chap5-Figure 2C; Chap5-Figure 2D). For each fruit lot of *S. spinosa* fruits (Chap5-Figure 3A; Chap5-Figure 3B), the shells of the fruits were also broken. Fruit puree and fruit juice were extracted using centrifugation (Chap5-Figure 3C) and steel steam extraction (Chap5-Figure 3D), respectively. In the case of fruit juice extraction by steam, the residual pulp was separated from seeds and weighed fresh. Thereafter, shell, pulp, and seeds from all the eight lots were oven-dried at 85 °C for 72 hours and their dry biomasses were determined.

Chap5-Figure 2: Measurements of fresh biomass of fruits (A), shell (B), seeds (C), and pulp (D) of a group of 50 fruits of *Strychnos madagascariensis* species.

Chap5-Figure 3: Harvesting of fruits (A), separation of components (B); and extraction of puree (C) and juice (D) from fresh fruits of *Strychnos spinosa*.

5.4.3. Statistical analysis

For individual fruit data (Dataset 1; Akweni et al. 2021), statistical dispersion parameters were calculated. Mean values of fresh biomass and diameter of individual fruits of each species and their respective standard deviations were determined. For grouped fruit data (Dataset 2; Akweni et al. 2021), the mean biomass values of each fruit component, including their standard deviations, were calculated for each species. These mean values were then added together and presented in proportions based on the average total biomass of lots of each species. Thereafter, these proportion values were applied to individual fruit data to generate the fresh biomass of each fruit component. The dry biomasses of the oven-dried fruit components (excluding puree and juice of *S. spinosa*) were used to calculate their respective moisture contents. The calculated moisture content values of fruit components were then applied to individual fruit data to convert the fresh biomass into dry biomass. Carbon stocks of fruit components were obtained by dividing their dry biomasses by two (Jana et al. 2009; Paladinić et al. 2009; Chavan and Rasal 2011). The dry biomass and carbon stocks of *S. spinosa* fruits did not include the puree and juice.

Regression technics were used as an alternate method to derive dry biomass and carbon stocks of fruit components. A simple linear regression model was fitted to individual fruit data (using the ordinary least squares method) to derive biomass and carbon stocks from fruit diameter. The residual standard error (RSE), the coefficient of determination (R^2), and the correlation factor (r) were calculated for each regression. Student T-test was used to compare the values of dry biomass (and carbon stocks) derived by proportions and those derived by regression.

The moisture content (MC; Chap5-Equation 1), the Student test (T-test; Chap5-Equation 2), and the standard deviations of mean values (SD; Chap5-Equation 3) were obtained using the following expressions:

$$\text{MC} = \frac{FB - DB}{FB} \qquad \text{(Chap5-Equation 1)}$$

$$\text{T-test} = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{(S^2\,(\frac{1}{n_1} + \frac{1}{n_2}))}} \qquad \text{(Chap5-Equation 2)}$$

$$\text{SD} = \sqrt{\frac{\sum(x_i - \overline{x}\,)^2}{n-1}} \qquad \text{(Chap5-Equation 3)}$$

where *FB* and *DB* respectively represent the fresh biomass and the dry biomass of a given fruit component (in g; Chap5-Equation 1). The terms $\overline{x}_1$ and $\overline{x}_2$ represent the compared mean values of a given variable of *S. madagascariensis* and *S. spinosa*, respectively. The term *S* is the pooled standard error of the variable of the two species being compared and n_1 and n_2 represent the number of fruits for each of the species (Chap5-Equation 2). The terms x_i, $\overline{x}$, and n represent the value (of a given variable) of each fruit (or group of fruits) in the considered data set, the mean value of the considered variable, and the number of fruits (or lots) in the considered data set, respectively (Chap5-Equation 3). All the statistical analyses were carried out using the R-software (R DEVELOPMENT CORE TEAM 2014).

5.5. Results

5.5.1. Dispersion parameters of individual fruits

Fresh biomass of individual *S. madagascariensis* fruits varied between 79.8 g and 796.0 g with a mean value of 356.6 g. The fruit diameter ranged from 5.5 cm to 11.4 cm with a mean value of 8.2 cm. For *S. spinosa* fruits, the fresh biomass varied between 154.5 g and 1113.4 g with a mean value of 441.9 g. The fruit diameter ranged from 6.1 cm to 12.5 cm (Chap5-Table 1). The T-test applied to make a comparison between the mean values of fresh biomass of individual fruits of *S. madagascariensis* and *S. spinosa* gave a significant *p-value* (Chap5-Table 1). The T-test applied to compare the mean values of fruit diameter of *S. madagascariensis* and *S. spinosa* gave a non-significant *p-value* (0.1509).

Chap5-Table 1: Dispersion parameters of individually measured fruit variables per species. The standard deviation (SD) and the test of Student (T-test) are provided for the mean values. The measure of the T-test probability (*p-value*) is reported at 95 % confidence interval where "*e*" is an exponential factor.

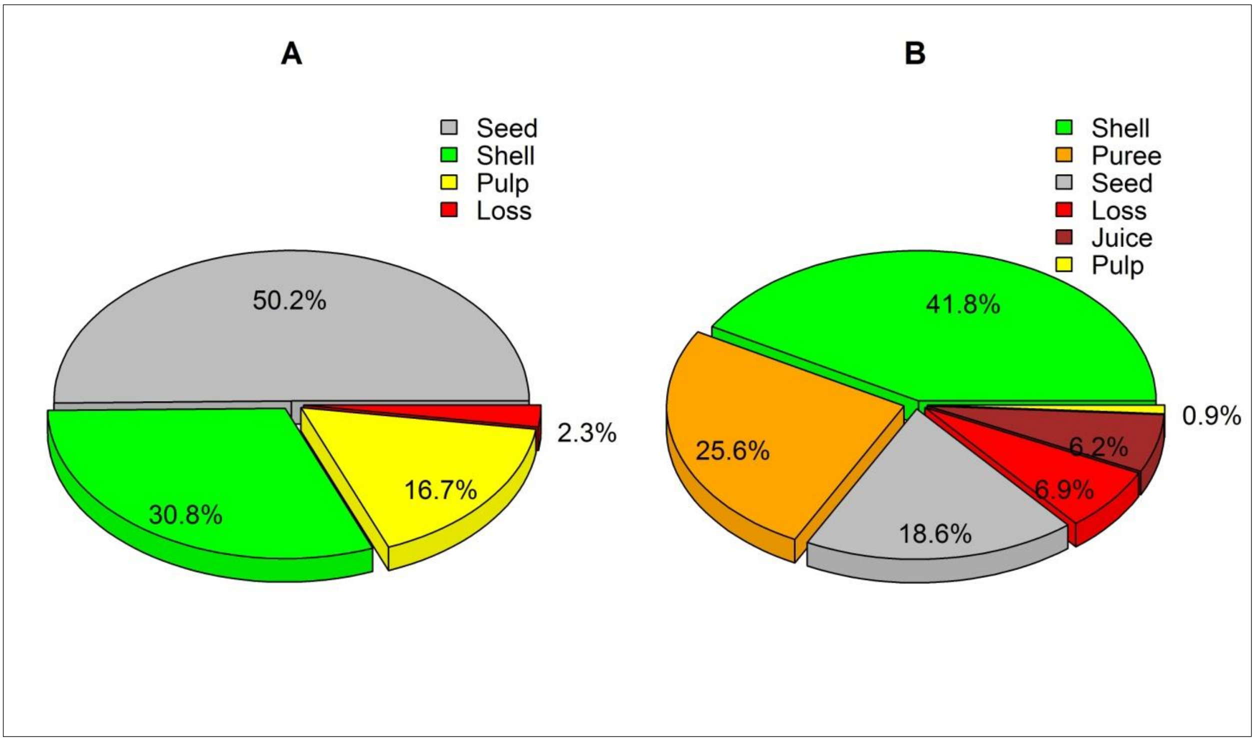
Dispersion parameters	Variables	Species		*p-value* (T-test)
		Strychnos madagascariensis	*Strychnos spinosa*	
Mean ± SD	Fruit biomass (g)	356.6 ± 123.4	441.9 ± 194.1	6.507*e*-06
	Fruit diameter (cm)	8.214 ± 0.94	8.386 ± 1.2	0.1509
Median	Fruit biomass (g)	346.3	417.4	
	Fruit diameter (cm)	8.15	8.20	
Minimum	Fruit biomass (g)	79.8	154.5	
	Fruit diameter (cm)	5.5	6.1	
Maximum	Fruit biomass (g)	796.0	1113.4	
	Fruit diameter (cm)	11.4	12.5	

5.5.2. Fresh biomass of fruit components

Fresh biomasses of Lot 1, Lot 2, Lot 3, and Lot 4 of *S. madagascariensis* fruits were 18375.97 g, 17717.48 g, 18014.95 g, and 17535.99 g, respectively. This represented on average 17911.10 g for these four lots (Chap5-Table 2). The mean fresh biomasses of the shell, pulp, and seeds of the four lots (each with 50 fruits) of *S. madagascariensis* fruits were 5511.86 g, 2986.90 g, and 8998.22 g which corresponded to 30.8 %, 16.7 %, and 50.2 %, respectively of the fruit biomass per lot. For *S. spinosa* fruits, fresh biomasses of Lot 5, Lot 6, Lot 7, and Lot 8 were 19770.66 g, 20040.16 g, 20364.05 g, and 21482.05 g, respectively. The mean fresh biomass of these four lots of *S. spinosa* fruits was 20414.23 g. The mean fresh biomasses of the shell, pulp, seeds, puree, and juice were 8526.55 g, 189.48 g, 3795.44 g, 5229.30 g, and 1273.77 g which respectively represented in terms of proportions 41.8 %, 0.9 %, 18.6 %, 25.6 %, and 6.2 % of the fruit biomass per lot. There was on average 414.12 g and 1399.69 g of loss of materials for fruit lots of *S*. *madagascariensis* and *S*. *spinosa*, respectively. Chap5-Figure 4 displays proportions of fresh biomass of fruit components of *S*. *madagascariensis* and *S*. *spinosa*.

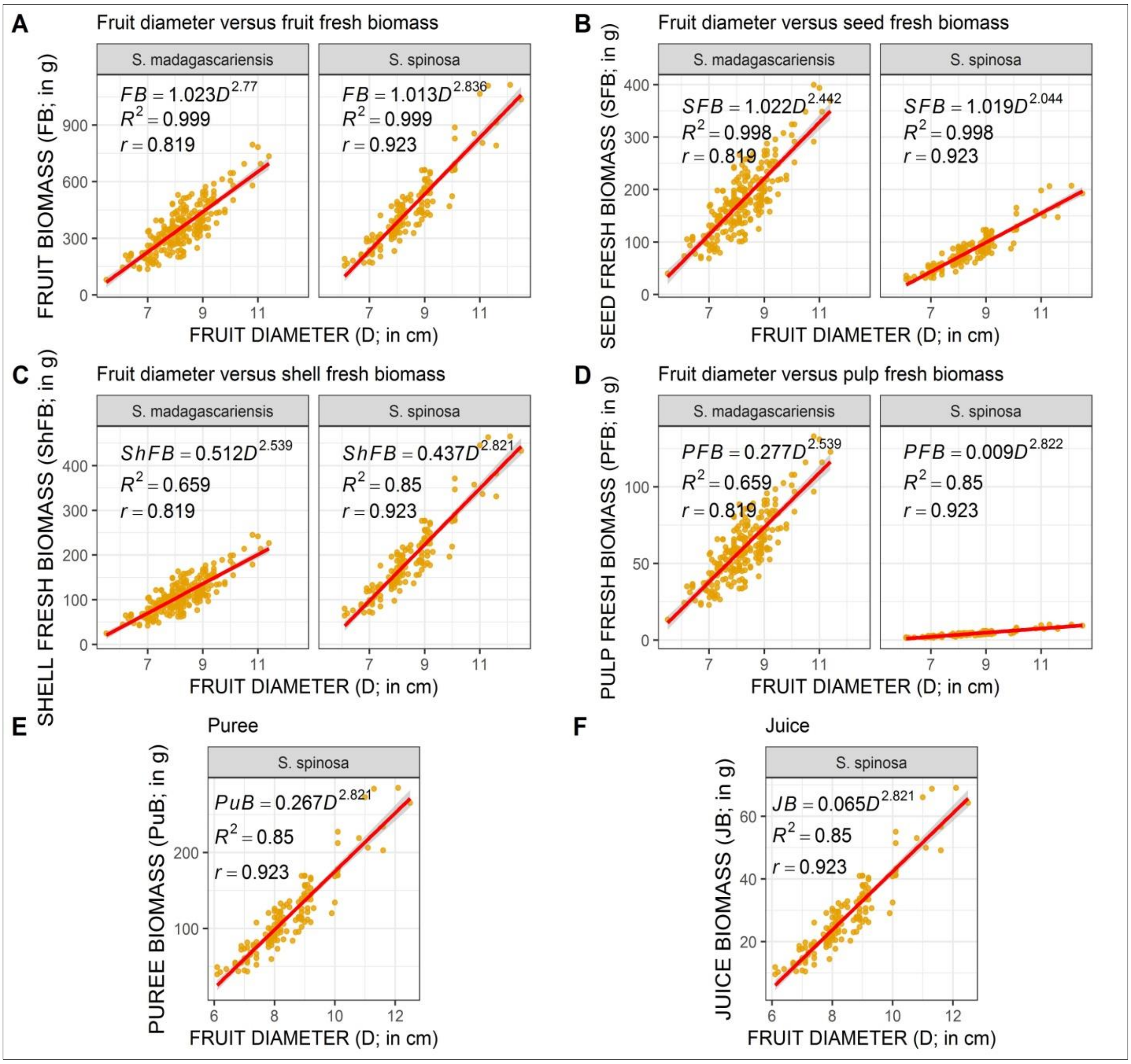
Chap5-Table 2: Measured fresh biomass (in g) of fruit components of *Strychnos madagascariensis* and *Strychnos spinosa* per lot of 50 fruits each. The standard deviation is given for the mean values.

Lot	Shell	Pulp	Seeds	Puree	Juice	Loss	Total per Lot
Strychnos madagascariensis							
Lot 1	5879.60	2810.51	9226.02	-	-	459.84	18375.97
Lot 2	5261.99	3142.18	8801.34	-	-	511.97	17717.48
Lot 3	5421.54	3010.91	8931.41	-	-	651.09	18014.95
Lot 4	5484.30	2984.01	9034.10	-	-	33.58	17535.99
Mean	5511.86 ± 262.4	2986.90 ± 136.3	8998.22 ± 179.2			414.12 ± 266.2	17911.10 ± 367.4
Strychnos spinosa							
Lot 5	8301.13	179.33	3816.54	4970.48	1387.41	1115.77	19770.66
Lot 6	8420.02	187.20	3919.60	5743.77	901.84	867.73	20040.16
Lot 7	8200.41	203.45	3751.21	5241.61	1212.41	1754.96	20364.05
Lot 8	9184.64	187.95	3694.41	4961.34	1593.40	1860.31	21482.05
Mean	8526.55 ± 447.8	189.48 ± 10.0	3795.44 ± 96.6	5229.30 ± 366.7	1273.77 ± 292.7	1399.69 ± 483.7	20414.23 ± 752.0



Chap5-Figure 4: Fresh biomass proportion chart of fruit components of *Strychnos madagascariensis* (A) and *Strychnos spinosa* (B).

There was a linear relationship between fruit diameter and fresh fruit components of *S. madagascariensis* and *S. spinosa*. The coefficients of determination of the fitted equations were higher than 0.90 for the regressions that involved fruit fresh biomass (Chap5-Figure 5A) and seed fresh biomass (Chap5-Figure 5B) for both species. On the other hand, regressions that involved shell fresh biomass (Chap5-Figure 5C), pulp fresh biomass (Chap5-Figure 5D), puree biomass (Chap5-Figure 5E), and juice biomass (Chap5-Figure 5F) had coefficients of determination that were lower than 0.90 for both species. The correlation factor between fruit diameter and any of the fresh fruit components of *S. madagascariensis* was 0.819 whereas the correlation factor between fruit diameter and any of the fresh fruit components of *S. spinosa* was 0.923.



Chap5-Figure 5: Relationship between fruit diameter and fresh fruit components of *Strychnos madagascariensis* and *Strychnos spinosa*. The fitted linear equation (also drawn in red curve), the residual standard error (grey zone surrounding the red curve), the coefficient of determination (R^2), and the correlation factor (*r*) are given for each relationship.

5.5.3. Moisture contents of fruit components

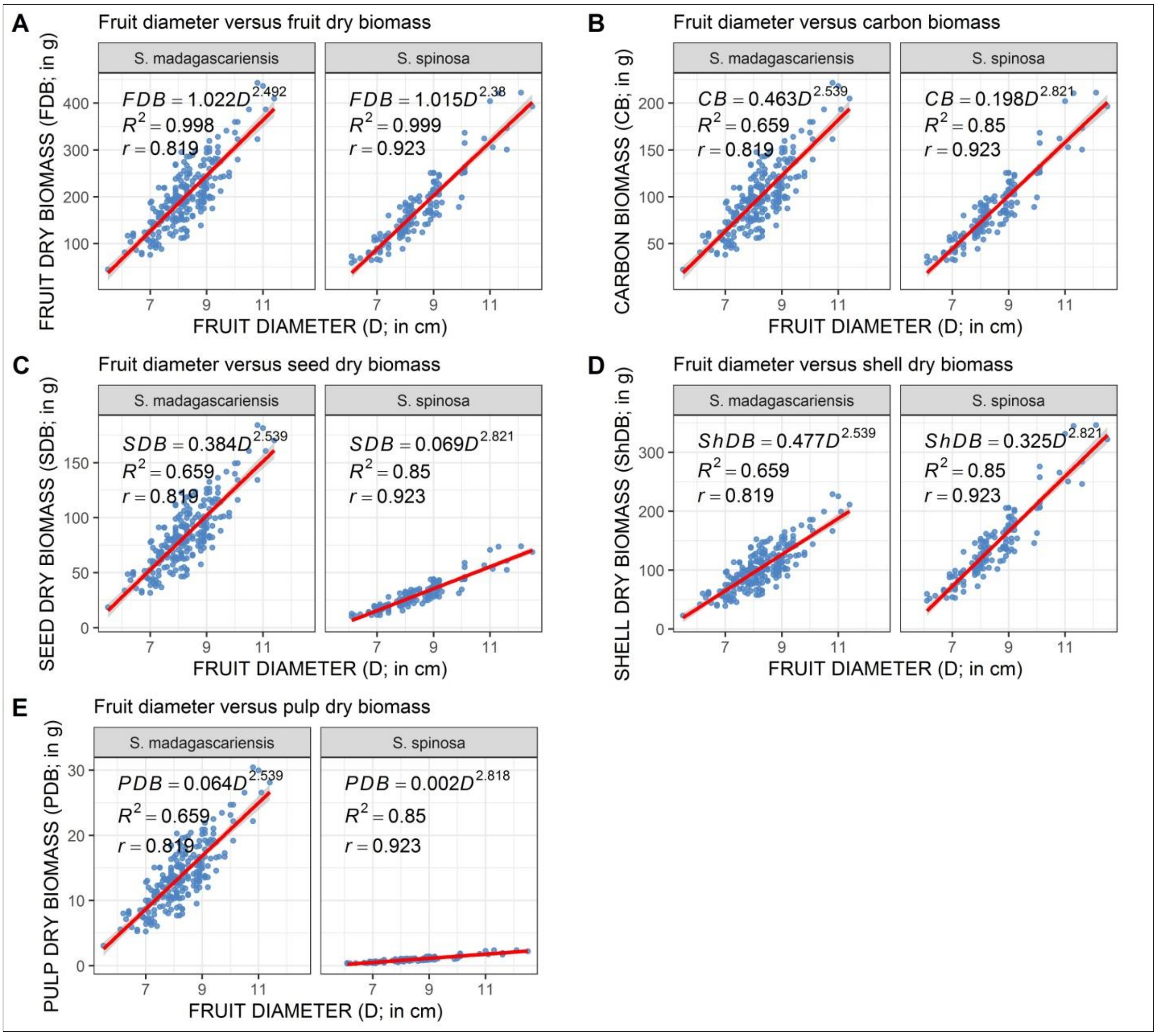
The mean dry biomasses of the shell, pulp, and seeds of the four lots of *S. madagascariensis* fruits were 5139.17 g, 682.24 g, and 4151.17 g which corresponded to moisture content values of 0.067, 0.771, and 0.539, respectively. For the lots of *S. spinosa* fruits, mean dry biomasses of the shell, pulp, and seeds were 6349.55 g, 44.64 g, and 1355.15 g which represented 0.256, 0.764, and 0.643 of moisture content, respectively (Chap5-Table 3).

Chap5-Table 3: Moisture content (MC) and dry biomass (DB) of fruit components of *Strychnos madagascariensis* and *Strychnos spinosa* per lot of 50 fruits each. The standard deviation is given for the mean values.

Lot	Shell		Pulp		Seed	
	DB (g)	MC	DB (g)	MC	DB (g)	MC
Strychnos madagascariensis						
Lot 1	5215.72	0.112	655.55	0.766	4531.36	0.508
Lot 2	5021.23	0.045	717.48	0.771	3851.63	0.562
Lot 3	5133.51	0.053	649.21	0.784	3956.41	0.557
Lot 4	5186.25	0.054	706.75	0.763	4265.28	0.527
Mean	5139.17 ± 85.6	0.067 ± 0.03	682.24 ± 34.8	0.771 ±0.009	4151.17 ± 308.3	0.539 ±0.03
Strychnos spinosa						
Lot 5	5901.23	0.289	41.36	0.769	1408.85	0.630
Lot 6	6244.17	0.258	43.51	0.767	1485.21	0.621
Lot 7	6310.12	0.230	48.21	0.763	1325.25	0.646
Lot 8	6942.68	0.244	45.51	0.757	1201.29	0.674
Mean	6349.55 ± 434.1	0.256 ± 0.03	44.64 ± 2.9	0.764 ± 0.005	1355.15 ± 121.6	0.643 ± 0.023

5.5.4. Dry biomass and carbon stocks of fruit components

The fruit dry biomass (FDB; in g) and the fruit diameter (D; in cm) were related by the following linear expressions $FDB = 1.022 \times D^{2.492}$ and $FDB = 1.015 \times D^{2.38}$; respectively for *S. madagascariensis* and *S. spinosa*, with the highest coefficient of determination ($R^2 = 0.99$; Chap5-Figure 6A). The fruit carbon biomass (CB; in g) and the fruit diameter were also related by a linear relationship for *S. madagascariensis* ($CB = 0.463 \times D^{2.539}$; $R^2 = 0.659$) and *S. spinosa* ($CB = 0.198 \times D^{2.821}$; $R^2 = 0.85$; Chap5-Figure 6B). The regressions between the fruit diameter and the seed dry biomass (Chap5-Figure 6C), shell dry biomass (Chap5-Figure 6D), or pulp dry biomass (Chap5-Figure 6E) had the same coefficient of determination per species ($R^2 = 0.659$ for *S. madagascariensis*; $R^2 = 0.85$ for *S. spinosa*). The correlation factor between fruit diameter and any of the dry fruit components of *S. madagascariensis* was 0.819 whereas the correlation factor between fruit diameter and any of the dry fruit components of *S. spinosa* was 0.923. Chap5-Table 4 presents all the fitted allometric equations that derive the biomass and carbon stocks of fruit components of *S. madagascariensis* and *S. spinosa*.

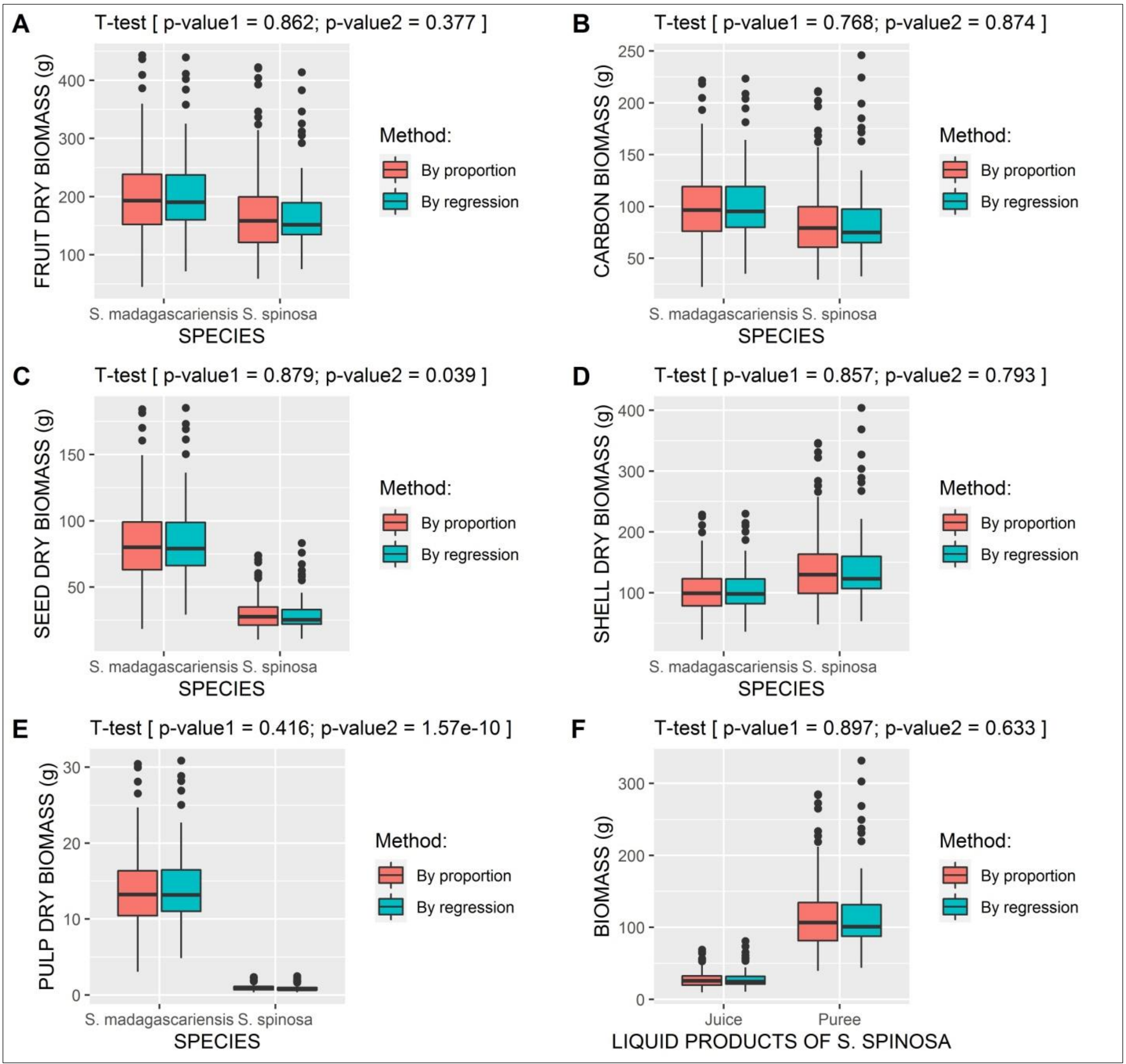


Chap5-Figure 6: Relationship between fruit diameter and dry fruit components of *Strychnos madagascariensis* and *Strychnos spinosa*. The fitted linear equation (also drawn in red curve), the residual standard error (grey zone surrounding the red curve), the coefficient of determination (R^2), and the correlation factor (r) are given for each relationship.

Chap5-Table 4: Allometric equations deriving the biomass (B; in g) and carbon stocks (CS; in g) of fruit components of *Strychnos madagascariensis* and *Strychnos spinosa* from the fruit diameter (D; in cm).

Component	*Strychnos madagascariensis*		*Strychnos spinosa*	
	Fresh biomass	Dry biomass	Fresh biomass	Dry biomass
Shell	$B = 0.512 \times D^{2.53}$	$B = 0.477 \times D^{2.53}$	$B = 0.437 \times D^{2.82}$	$B = 0.325 \times D^{2.82}$
Pulp	$B = 0.277 \times D^{2.53}$	$B = 0.064 \times D^{2.53}$	$B = 0.009 \times D^{2.82}$	$B = 0.002 \times D^{2.81}$
Seeds	$B = 1.022 \times D^{2.44}$	$B = 0.384 \times D^{2.53}$	$B = 1.019 \times D^{2.04}$	$B = 0.069 \times D^{2.82}$
Puree	-	-	$B = 0.267 \times D^{2.82}$	-
Juice	-	-	$B = 0.065 \times D^{2.82}$	-
Fruit	$B = 1.023 \times D^{2.77}$	$B = 1.022 \times D^{2.49}$	$B = 1.013 \times D^{2.83}$	$B = 1.015 \times D^{2.38}$
Fruit Carbon	$CS = 0.463 \times D^{2.53}$		$CS = 0.198 \times D^{2.82}$	

The Student T-test comparing the mean values of biomass derived by proportion and by regression methods indicated that the parameter *p-value* was higher than 0.05 for fruit dry biomass (Chap5-Figure 7A), fruit carbon biomass (Chap5-Figure 7B), and shell dry biomass (Chap5-Figure 7D), for both species. The same trend was also observed in the biomasses of Juice and puree of *S. spinosa* (Chap5-Figure 7F). On the other hand, *p-value* was lower than 0.05 in the comparison of seed dry biomass (Chap5-Figure 7C) and pulp dry biomass (Chap5-Figure 7E) of *S. spinosa* generated by proportion and by regression methods.



Chap5-Figure 7: Box plots of dry fruit components biomass of *Strychnos madagascariensis* and *Strychnos spinosa* per method of biomass derivation. Horizontal lines (inside boxes) represent the mean biomass per derivation method and vertical dots display the dispersed biomass. Reports of Student test (T-test) are given per species.

5.6. Discussion

5.6.1. Fruit size and fruit biomass

One of the major limitations to the commercialization of *S. madagascariensis* and *S. spinosa* is the scarcity of data on the size of their fruits (Rodrigues et al. 2018) and the relative proportions of the fruit components that can be converted into fruit products. In the present study, there were wide variations in the sizes of the fruits in both species in terms of both their fresh biomass and diameter. In *S. spinosa*, the largest fruit (1113.4

g) was seven times the biomass of the smallest fruit measured, and the diameter of the largest fruit (12.5 cm) was two times that of the smallest fruit. In the case of *S. madagascariensis*, the biomass of the largest fruit (796 g) was 10 times that of the smallest fruit, and the diameter of the largest fruit (11.4 cm) was twice that of the smallest fruit. There was a significant difference in the mean values of fruit fresh biomass between *S. spinosa* and *S. madagascariensis* ($p < 0.05$; Chap5-Table 1). This implied that the mean fresh biomass of fruits of *S. spinosa* was statistically higher than that of *S. madagascariensis* at 95 % confidence interval. The T-test results showed no significant differences in fruit diameter between *S. spinosa* and *S. madagascariensis* ($p > 0.05$; Chap5-Table 1). This result was unexpected, but it means the fruit diameter is a parameter that cannot be used to differentiate between the two species. The wide variations between the fruits could not be explained because of the nature of the study, but there are a number of factors at play that could account for the wide variations. They include genetic differences, plant size, soil fertility, fruit load, and water availability. The contributions of these factors to the wide variations in fruit fresh biomass and diameter need to be determined in future studies.

5.6.2. Fresh biomass of fruit components

This study showed that for a set of fruits of *S. madagascariensis* species, the fresh biomasses of the shell, pulp, and seeds corresponded on average to 30.8 %, 16.7 %, and 50.2 %, respectively, of the total biomass of the fruit. On the other hand, for *S. spinosa* fruits, the fresh biomasses of shell, puree, seeds, juice, and pulp corresponded to 41.8 %, 25.6 %, 18.6 %, 6.2 %, and 0.9 %, respectively, of the total biomass of the fruit (Chap5-Figure 4). As they are proportions, they can therefore be applied to the fresh biomass of fruits regardless of their number. However, material losses must be provisioned as they are inevitable during the process of separating fruit components. This can be due to small wastes during processing or to a gradual loss of moisture from the fruit or its components. As *S. spinosa* fruits contain puree (Chap5-Figure 3C) and juice (Chap5-Figure 3D), which naturally possess high amounts of water, it was not surprising to observe a high loss of biomass in *S. spinosa* fruits compared to *S. madagascariensis* fruits. It should be noted that these proportion values of fruit components can vary depending on the methods used for the separation of the fruit components. For example, Rodrigues et al. (2018) reported that the juicy flesh of *S. spinosa* fruits can vary between 30 % and 45 %. This range is higher than what is reported in this study because the "juicy flesh", mentioned by Rodrigues et al. (2018), could have been composed of pulp and puree. This study considered them as separate entities. Separation techniques of fruit components are among the constraints to be solved (Ngadze et al. 2017). The separation methods used in this study are not refined industrial methods. They were applied with the intention of reproducing traditional methods used by locals to extract and market fruit juice.

Besides expressing the partitioning of fresh biomass of fruit components of *S. madagascariensis* and *S. spinosa* as proportions, regression is also an option in relating the components of the fruits. This study showed that the fresh biomass of each fruit component of *S. madagascariensis* and *S. spinosa* can also be derived using the linear regression equations that link the biomass of any of the fruit components to the fruit diameter. The quality of the fitted regression equations was good in terms of their coefficients of determination and the correlation factors (Chap5-Figure 5). Generally, regression models for fruit biomass estimations are developed for specific economic (Akweni et al. 2020) and ecologic purposes. In the context of the current study, the regression models for deriving fruit biomass from fruit diameter provide a non-destructive method of estimating C channeled to fruits in ecological studies. In cases where fruits are harvested from the forest for commercial purpose, the regression models for deriving fruit biomass are useful in estimating none-destructively fresh fruit yield of a forest stand in relation to its commercial value where the fruits are sold and eaten fresh in the markets (Rodrigues et al. 2018). The regression models for estimating biomass of fruit components also have important applications under commercial production/cultivation should the species be domesticated and commercialized. In this regard, the regression equations deriving seed fresh biomass (Chap5-Table 4; Chap5-Figure 5B), shell fresh biomass (Chap5-Figure 5C), and pulp fresh biomass (Chap5-Figure 5D) are of interest in estimating waste from processing the fruit for fruit juice and jams (*S. spinosa*), or food products made from the fruit pulp (*S. madagascariensis*). The regression equations for deriving fruit fresh biomass (Chap5-Table 4; Chap5-Figure 5A), puree (Chap5-Figure 5E; for *S. spinosa*), and juice (Chap5-Figure 5F; for *S. spinosa*) are important in estimating the amount of specific commercial products that can be made from these fruit parts. In any of these cases above, deriving fruit fresh biomass from fruit diameter is important for the non-destructive determination of biomass of individual fruits. Likewise puree and juice, the derivation of their biomasses from fruit diameter is crucial in the quick evaluation of their yield without having to resort to time-consuming processes of extracting them.

Nevertheless, the point clouds of the graphs E and F of Chap5-Figure 5 look identical. It is important to mention that these similarities of point clouds are normal and they are due to the methods that were used to derive the amount of juice and puree in individual fruits. This was done using a fixed proportion value (obtained from a measurement of 4 lots of 50 fruits each). Consequently, fruits of different sizes and masses are supposed to contain the same proportion (in %) of juice and puree following their individual masses. This does not mean that the amount of juice and puree is the same in each fruits. They differ based on the weight (mass) of each fruit. The trend reflected in those graphs looks identical because of the use of proportion values, but there is a distinct difference in the y-axis values.

5.6.3. Moisture contents of fruit components

Fruits are components of trees that are subject to seasonal production. They are therefore elements of reference for the evaluation of carbon (C) dynamics. However, to assess the amount of C sequestrated by fruits, it is necessary to know their dry biomass. Dry biomass can also be obtained from fresh biomass by using formulas that involve specific density or moisture content (Alemdag 1981; Rondeux 1999; Bauwens and Fayolle 2014). Data from the present study revealed that moisture contents of the shell, pulp, and seeds of *S. madagascariensis* fruits are different with the shell having the least and the pulp the most (Chap5-Table 3). The same trend was observed for *S. spinosa*. The differences in moisture content between the shell and the pulp were 0.704 for *S. madagascariensis* and 0.508 for *S. spinosa.* This is expected because the hard shell acts as a barrier to water loss by fruit. Surprisingly, the fruit pulp of the two species had almost equal moisture content (Chap5-Table 3) despite that the fruit pulp of *S. spinosa* was fully engorged with juice. This can be explained by the procedure that was used to separate the pulp from the juice. In fact, fruit pulp of *S. spinosa* was obtained after the extraction of juice. It is therefore possible that a significant amount of water in the pulp could have been removed together with the extracted juice.

5.6.4. Dry biomass and carbon stocks of fruit components

Currently, estimating the amount of biomass and carbon stocks sequestrated by forest ecosystems is part of international priorities for the evaluation of their contributions to the purification of the atmosphere (Chave et al. 2004; Ryan et al. 2011). In savannah woodlands, fruit trees contribute to carbon sequestration through their above-ground and below-ground biomass (Mugasha et al. 2013). Unfortunately, the carbon stocks stored in fruits are rarely investigated despite the considerable annual production of fruit biomass by fruit trees. This is because the carbon stocks stored in fruits are rapidly turned back to the atmosphere. Also, methods that derive the fruit dry biomass and carbon stocks have never been developed for most fruit tree species. This study showed that fruit dry biomass is related to fruit diameter by a linear relationship. This implies that the fruit dry biomass of *S. madagascariensis* and *S. spinosa* can be derived from their fruit diameter using the regression equations mentioned in Chap5-Table 4. This also holds for fruit carbon stocks (Chap5-Figure 6B). It was proven that the dry biomass of each fruit component was positively correlated to the fruit diameter. However, the correlation factor between fruit diameter and dry biomass of any of the fruit components was the same per species. This can be explained by the fact that the dry biomass of each fruit component was obtained from the fresh biomass which was previously derived by proportion values.

From the above, it was necessary to compare both methods used in this study to derive dry biomass and carbon stocks of fruit components. The results of T-test indicated that there was no difference between the mean values of fruit dry biomass (Chap5-Figure 7A), fruit carbon stocks (Chap5-Figure 7B), and shell dry biomass (Chap5-Figure 7D) that were generated by proportion and by regression methods. In other words, these two methods are valid and can therefore be used to derive dry biomass and carbon stocks of the above-mentioned fruit components of *S. madagascariensis* and *S. spinosa*. In addition, the derivation of juice and puree of *S. spinosa* by both methods was unbiased (Chap5-Figure 7F; *p-value* > 0.05). However, there was a significant difference in the mean values of seed dry biomass (Chap5-Figure 7C; *p-value* < 0.05) and pulp dry biomass (Chap5-Figure 7E; *p-value* < 0.05) of *S. spinosa* that were calculated by way of proportions and those that were generated via regression. The regression methods significantly underestimated the seed dry biomass and pulp dry biomass of *S. spinosa* at 95% confidence interval. The differences in the derivation of pulp dry biomass of *S. spinosa* can simply be explained by the issues of moisture content and separation procedure of pulp that were discussed in the previous section. As for the differences between the two methods in the derivation of seed dry biomass of

S. spinosa, this study could not provide a plausible explanation. Further investigations are necessary to determine the variability of moisture content within seeds of *S. spinosa*.

5.7. Conclusion

This study established techniques that make it possible to derive biomass allocation and carbon stocks of fruit components of *S. madagascariensis* and *S. spinosa*. In the advent of commercializing the fruits of the two species, these findings will be useful in estimating the commercial value of *S. madagascariensis* and *S. spinosa* fruits and their products throughout their value chain following harvesting. In addition, the data can be used to assess the contribution of these fruit-bearing species to the carbon dynamics of savannah woodlands.

CHAPTER 6: ESTIMATION OF *STRYCHNOS MADAGASCARIENSIS* AND *S. SPINOSA* FRUIT BIOMASS PRODUCTION IN A SAVANNAH WOODLAND

6.1. Full title

Estimating the fruit biomass production potential of the Central Portions of the Umhlabuyalingana Municipality in KwaZulu-Natal, South Africa: Case of *Strychnos madagascariensis* and *S. spinosa*.

6.2. Abstract

The Central Portions of the Umhlabuyalingana Municipality (CPUM) are among the poorest rural areas in South Africa. Paradoxically, its natural vegetation has the highest amount of fruit tree species whose production potential has never been investigated. The study reported in this chapter aimed to evaluate the production potential of the CPUM in terms of fruit biomass of *Strychnos madagascariensis* and *S*. *spinosa*. Field surveys of trees were conducted in eight 0.25-ha square plots following an East-West distance gradient of 1.4 km. The diameter at breast height (DBH), the total height, and the canopy size of trees were measured. The fruit biomass of trees (with DBH ≥ 2 cm) was estimated using existing fruit-based allometric equations. Unpaired one-way analysis of variance (ANOVA) was performed to compare the distribution of mean fruit biomasses in the plots. The *ESRI Calculate Geometry* tool of ArcGIS was used to calculate the total surface of the study area, which served to obtain its global fruit biomass production. The results indicated that there were strong disparities in the distribution of fruit biomass at both plot and species levels, with a strong dominance of younger trees in the first DBH class (2 ≤ DBH ≤ 6.8 cm). The productivity of the CPUM was on average 935.2 ± 532 kg ha^{-1} and 1211.8 ± 971 kg ha^{-1} of fresh fruit biomass, respectively for *S. madagascariensis* and *S. spinosa*. Based on the total surface of the CPUM (14107.12 ha), this represented a maximum production potential of 13192.98 tons (t) and 17095.01 t of fresh fruit biomass for *S. madagascariensis* and *S. spinosa*, respectively. This study concluded that the CPUM had a considerable fruit biomass production potential to support an industrial commercial harvest of the fruits from the wild which can create employments for local communities and reduce poverty.

Keywords: Fruit biomass; Umhlabuyalingana municipality; *Strychnos madagascariensis*; *Strychnos spinosa*.

6.3. Introduction

The Central Portions of the Umhlabuyalingana Municipality (CPUM) are located in the UMkhanyakude district of the KwaZulu-Natal province in South Africa. Both the municipality and the district have the highest poverty levels in KwaZulu-Natal (Harmse 2010; Kleynhans and Coetzee 2019). About 77% of the inhabitants of the UMkhanyakude district experience severe poverty (Drimie et al. 2008; IDP 2018; SDF 2018). UMkhanyakude is one of the most vulnerable districts in South Africa (Mthembu and Hlophe 2020), both socially and economically (Khumalo-Mbonambi et al. 2014). In the northern part of the district, specifically in the CPUM, there are 24% of underweight and malnourished children (Govender et al. 2017; Naidoo et al. 2020). Agriculture is the major means of subsistence for local communities (Schoeman et al. 2010; Govender et al. 2017). However, agricultural development in the CPUM is seriously hindered by the poor quality of the soils which are mostly sandy (Botha and Porat 2007). This is among the reasons for the high rate of chronic malnutrition in the CPUM. A large part of the CPUM is underdeveloped and rural. In addition, there are very few livelihood options and little economic activity in the municipality (Biyela et al. 2018). Thus far, the municipality does not contribute much to the industrial development of KwaZulu-Natal province (SDF 2018).

Surprisingly, while the municipality is considered the most impoverished in South Africa (Mpanza and Govender 2017; Mthembu and Hlophe 2020), its natural vegetation has huge unexploited economic potentials. The Umhlabuyalingana municipality is endowed with a large expanse of savannah woodland (Jewitt 2018; Mucina 2018), which has a high diversity of indigenous fruit tree species and suffrutices (Mucina and Rutherford 2006; Boon 2010). The most important fruit tree species include the green monkey orange (*Strychnos spinosa*), the black monkey orange (*Strychnos madagascariensis*), the mangosteen (*Garcinia livingstonei*), the natal apricot (*Dovyalis longispina*), the wild-medlar (*Vangueria infaustia*), the wild plum (*Harpephyllum caffrum*), the large sour plum (*Ximenia caffra*), and the Christmas bells (*Trichilia emetica*; also called mafura or water plant). The suffrutices include the lemon-rope (*Salacia krausii*), the mobola plum (*Parinari curatellifolia*), among others. These fruit-bearing species have a high potential for commercial harvest from the wild which can boost household economies (Nkosi et al. 2020). The fruits such as *S. spinosa* and *Garcinia livingstonei* are sold fresh in the markets while other fruits such as *S. madagascariensis* and *Vangueria infaustia* are processed into dried products that are sold in small containers (Ngadze et al. 2017; Shai et al. 2020). They contain several alkaloids (Gautam et al. 2021; He et al. 2020; Semenov et al. 2020) and present an alternative source of food and income for local communities (Sulieman and Mariod 2019; van Rayne et al. 2020). *Strychnos spinosa* is the most appreciated fruit tree in KwaZulu-Natal (Nkosi et al. 2020). Its valuable fruit has an edible and juicy pulp (Ngadze et al. 2019) which is surrounded by brown seeds (Mizrahi et al. 2002; Rodrigues et al. 2018; Avakoudjo et al. 2020). It is also used in traditional medicine (Ngemakwe et al. 2017; Beaufay et al. 2018; Hassan et al. 2020; Razzaq et al. 2020) and can treat several infectious diseases (Mors et al. 2000; Isa et al. 2014). Unfortunately, most of these indigenous fruits are not yet involved in agro-industrial and agribusiness development (Rodrigues et al. 2018). Industrial processing of fruits into juices, jams, and oils can generate additional revenues (Ngadze et al. 2017; Nchimbi 2020; Poojary and Passamonti 2020), create rural employments (Nkosi et al. 2020), and tackle food insecurity (Koffi et al. 2020). Besides, the proximity of rural commercial centres such as Mbazwana, Sikhemelele, Manguzi, and Mseleni offer a huge business opportunity for locals should they commercially harvest the fruits from the wild. Moreover, in the case of large-scale agro-industrial businesses, these centres might serve as places where processing and service support can be based.

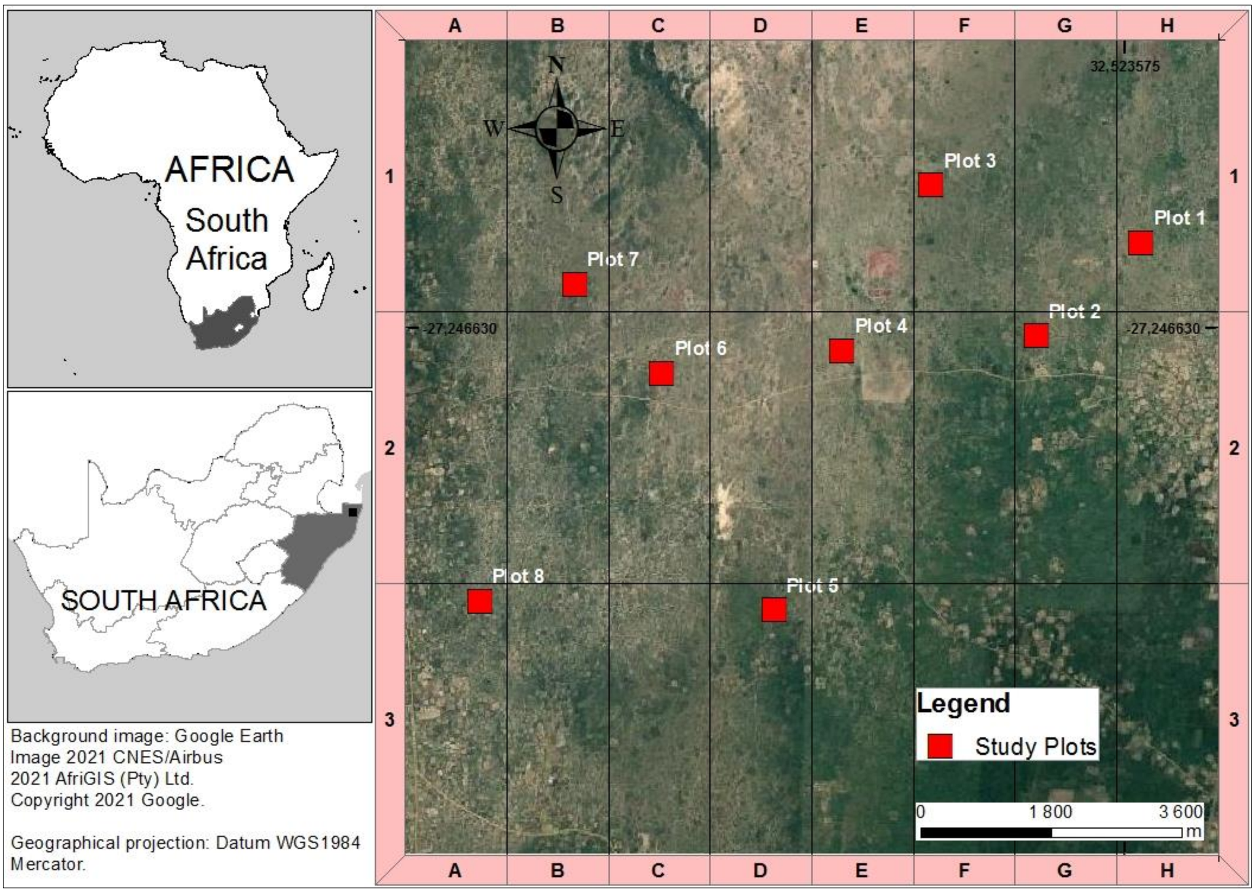
One of the major limitations in the development of agro-industrial businesses based on commercial harvesting of fruits from the wild is the difficulty to evaluate the fruit biomass production potential of a biome. Biomass refers to the weight of organic matter of living organisms (Focardi 2008; Houghton 2008; Basu 2018; Edomah 2018). In fruits, it represents the fresh or dry mass of the whole fruit organ. Biomass is one of the most fundamental measurements in ecology (Chave et al. 2004; Pearson and Brown 2005; Steinman et al. 2017). On the other hand, a biome is a large naturally occurring community of flora and fauna occupying a major habitat (Vlok and Euston-Brown 2002; Vlok et al. 2003). To estimate the above-ground biomass (AGB) of trees in a biome, three main stages are necessary. The first stage is the development of allometric equations that link tree parameters such as the diameter at breast height (DBH; Maniatis et al. 2011; Chidumayo 2013), the height (Mensah et al. 2017), and the wood specific density (Chave et al. 2005; Henry et al. 2010) to the tree biomass (Picard et al. 2012). This is usually done from a restricted sample size (Ebuy et al. 2011; Ryan et al. 2011). In the second stage, allometric equations will then be used to predict the AGB of trees in larger areas (Vieilledent et al. 2012). This will enable the calculation of the average biomass per surface unit. The last stage will refer to this average to obtain the global biomass in a biome (FAO, 2006). Likewise, the estimations of the fruit biomass production in a biome will require these three stages to be completed, but in this case, fruit-based allometric equations will be used instead (Peters et al. 1988).

Currently, studies that focus on the prediction of fruit yield using allometric techniques are scarce. Only recently, Akweni et al. (2020) developed fruit-based allometric equations for *S. madagascariensis* and *S*. *spinosa*. These equations make it possible to extend the estimations of fruit biomass of these species in the scale of a biome. The study reported in this chapter aims to estimate the fruit biomass production potential of the CPUM for *S. madagascariensis* and *S. spinosa*. These estimations are crucial in the process of developing agro-industrial projects based on the commercial harvesting of fruits from the wild. They will facilitate the evaluation of the economic value of savannah woodlands in KwaZulu-Natal based on the prices of fruits in the local markets or the products from the fruit. Also, the evaluations will provide guidance to investors and local communities in deciding on ventures relating to commercial harvesting of the fruits. Ecologically, estimating fruit biomass production in a biome enables the quantification of carbon (C) stocks sequestration by fruits. Although C sequestration is marginal in fruits (Sofo et al. 2005; Rodrigues et al. 2018), its evaluation can contribute to the understanding of C dynamics in savannah woodlands (Wu et al. 2012; Pérez-Piqueres et al. 2020).

6.4. Materials and methods

6.4.1. Sampling techniques and study plots

This study was conducted in the Central Portions of the Umhlabuyalingana Municipality (CPUM) covering a total area of 14107.12 ha. Its vegetation is dominated by natural savannah woodland formations (Jewitt 2018) which undergo a humid subtropical climate with a maximum temperature of 35 °C and a minimum temperature of 14 °C. The CPUM were subdivided into eight longitudinal sections (section A, B, C, D, E, F, G, and H; Chap6-Figure 1) and three latitudinal sections (section 1, 2, and 3; Chap6-Figure 1). Each longitudinal section had 1.4 km in width while each latitudinal section had 3.75 km in width. The plots were purposively sampled to cover both longitudinal and latitudinal gradients. A total of eight 0.25-ha square plots were installed following the longitudinal gradient (East-West direction). In other words, one plot was installed in each longitudinal section. Each latitudinal section was covered by three study plots except the third section which had only two plots. Chap6-Figure 1 displays the spatial distribution of study plots within the CPUM.



Chap6-Figure 1: Location map of study plots involving *Strychnos madagascariensis* and *Strychnos spinosa* species.

This study focused only on one vegetation type which is “savanna woodlands”. In such vegetation, it is reported that there is very little heterogeneity in terms of species composition and biomass production per hectare. Some authors have even established that one hectare of woodland produces on average 510 kg of fruit biomass (Campbell et al. 1996). When Strychnos species are involved, this average can increase because a single *Strychnos* tree can yield up to 75 kg of fresh fruit (Akweni et al. 2020). What did matter the most in this study was the quality of the plots sampled (whether they are reflective of the vegetation under study), but not the quantity of plots. In addition, for logistical and financial reasons, I could not survey more plots. It should however be noted that more plots would have allowed a better estimation of the standard deviation.

6.4.2. Field survey and fruit biomass measurements

In each study plot, all the trees of *S. madagascariensis* and *S. spinosa* species with DBH ≥ 2 cm were measured. Tree measurements included the diameter at breast height (DBH), the total height, the canopy size, and the fruit biomass. The fruit biomass of each tree was estimated using the fruit-based allometric equations developed by Akweni et al. (2020). Chap6-Equation 1 and Chap6-Equation 2 below were used to estimate fruit biomass for *S. madagascariensis* and *S. spinosa*, respectively.

$$FB = 1.0243 \times DBH^{1.1841} \qquad \text{(Chap6-Equation 1)}$$

$$FB = 1.0297 \times DBH^{1.1956} \qquad \text{(Chap6-Equation 2)}$$

where FB represents the estimated fresh fruit biomass of a tree (in kg) and *DBH* is the diameter at breast height of a tree (in cm; Akweni et al. 2020). To stay within the DBH range covered by these fruit-based allometric equations, trees with a DBH < 2 cm were not considered. Generally, for *Strychnos* species, trees that are smaller than 2 cm do not fruit. In addition, trees larger than 35 cm DBH are scarce. For multi-stemmed trees, mostly met with *S. madagascariensis*, the DBH of each stem was measured and I have considered the mean value.

6.4.3. Statistical analysis

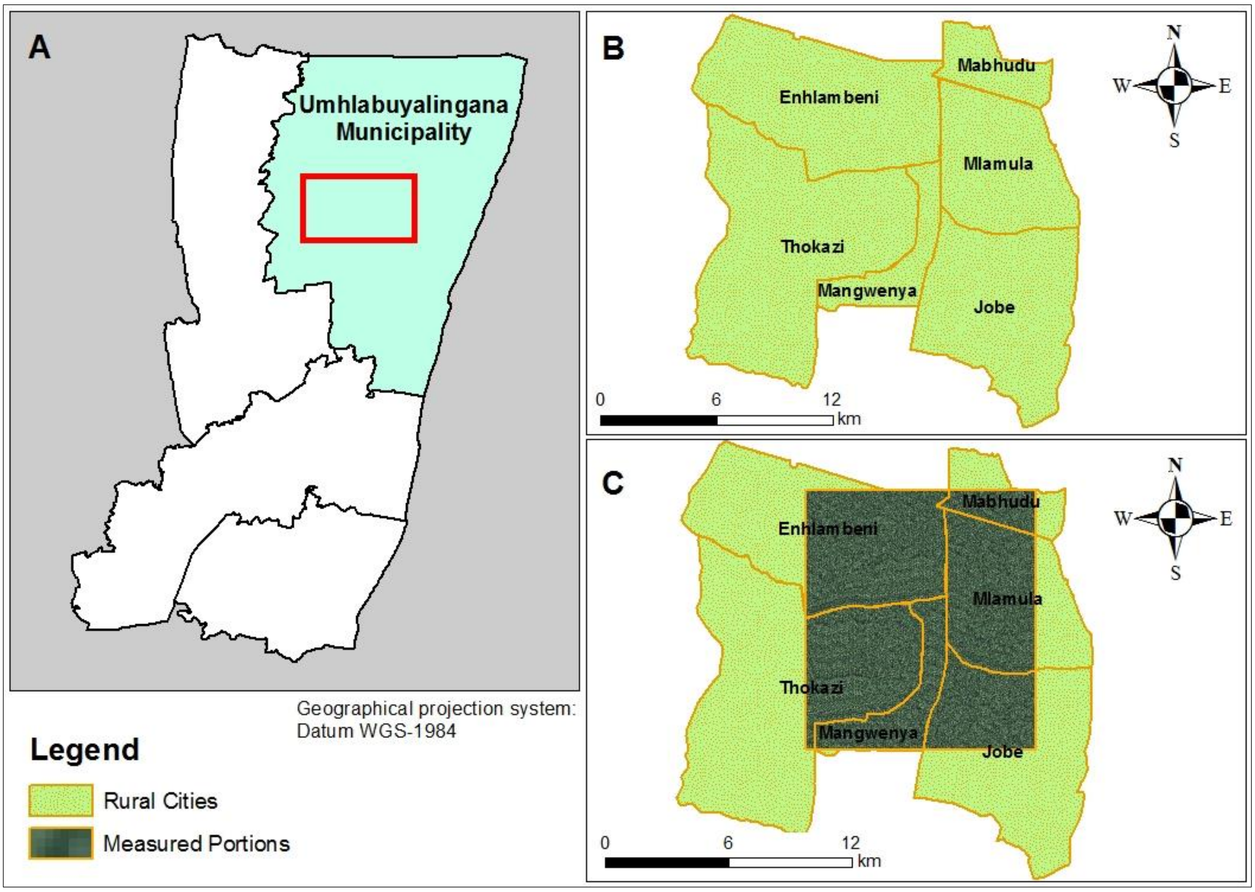
The estimated fruit biomasses of trees in a plot were used to calculate the mean fruit biomass of that plot. Unpaired one-way analysis of variance (ANOVA) was performed to compare the distribution of mean values of fruit biomass in the study plots. The normal distribution of data was checked before applying the ANOVA test. The estimated fruit biomass of each tree was added together to obtain the total fruit biomass of a plot. This total per plot was then considered to generate the global mean fruit biomass of the plots. This global value, obtained from 0.25-ha plots, was then extrapolated to 1-ha plots. This extrapolated value was considered as the average fruit biomass production capacity of any 1-ha surface within the CPUM. These calculations were done for each of the two studied species. Standard deviations (SD; Chap6-Equation 3) were determined for each mean value. Graphic exploration of the data was done using the GGPLOT2 package (Wickham 2016). All the analyses were run in the R-studio platform (R DEVELOPMENT CORE TEAM 2018).

$$SD = \sqrt{\frac{\sum(x_i - \overline{x})^2}{n-1}} \qquad \text{(Chap6-Equation 3)}$$

In Chap6-Equation 3, the symbols x_i, $\overline{x}$, and n respectively represent the fruit biomass of a tree (or the total fruit biomass in a plot), the mean fruit biomass in a plot (or for all the plots), and the total number of trees in a plot (or the total number of plots).

6.4.4. Cartographical analysis

Cartographical analyses were conducted using ArcGIS software and Google-map resources. The administrative boundaries of rural cities that cover the study area were digitized in ArcGIS interface using Landsat-8 cartographic data of Google-map. The area of each rural city was calculated using the *ESRI Calculate Geometry* tool. This area was then multiplied by the average amount of fruit biomass production per surface unit (by species) to generate a global estimate of fruit biomass production in the CPUM. Chap6-Figure 2 presents the digitized rural cities and the area considered in the estimations of global fruit biomass production.

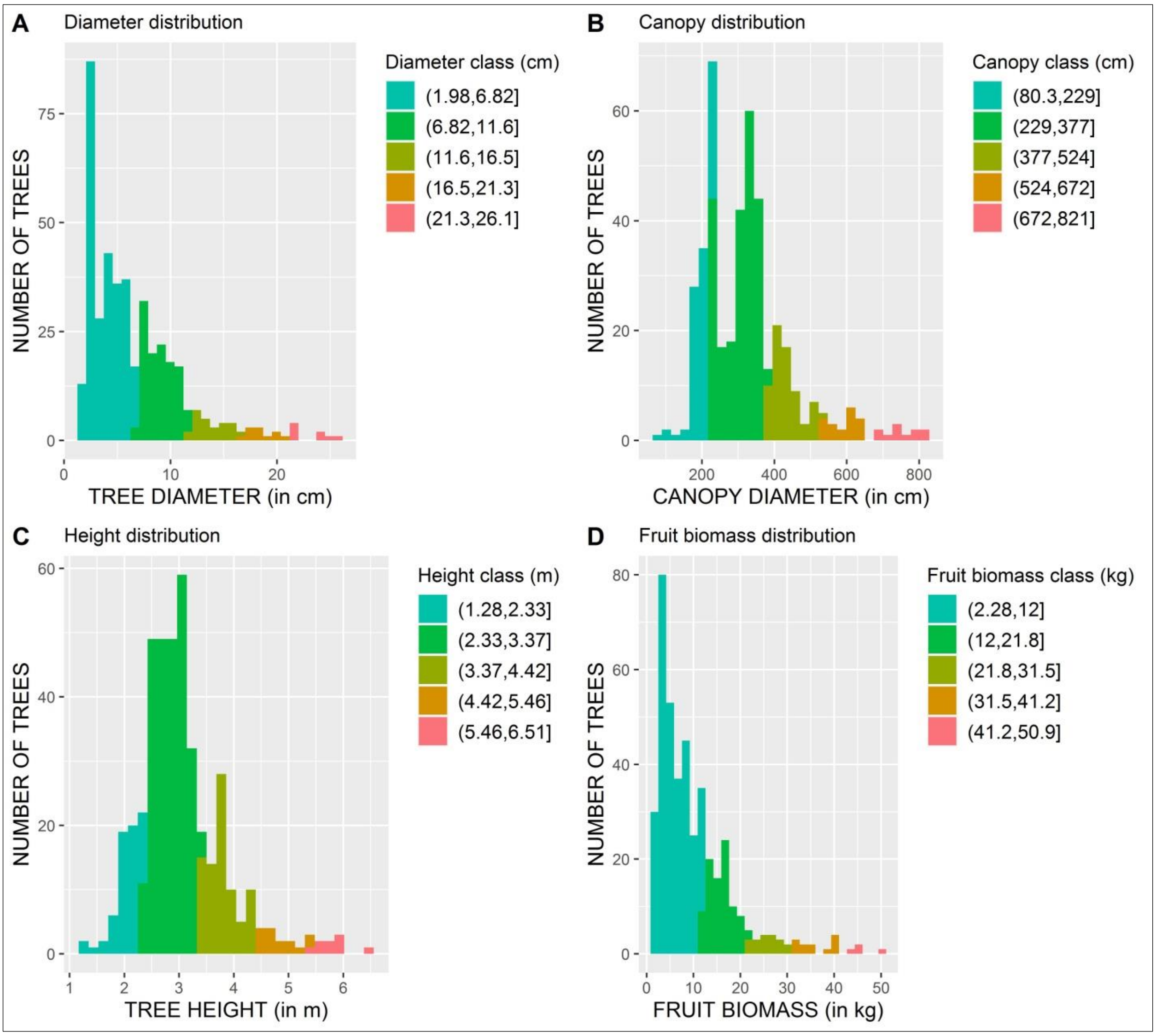


Chap6-Figure 2: Map presenting the Central Portions of the Umhlabuyalingana Municipality (framed in red) within the Umkhanyakude district (A), the digitized local cities (B), and the surface considered for fruit biomass estimations (C).

6.5. Results

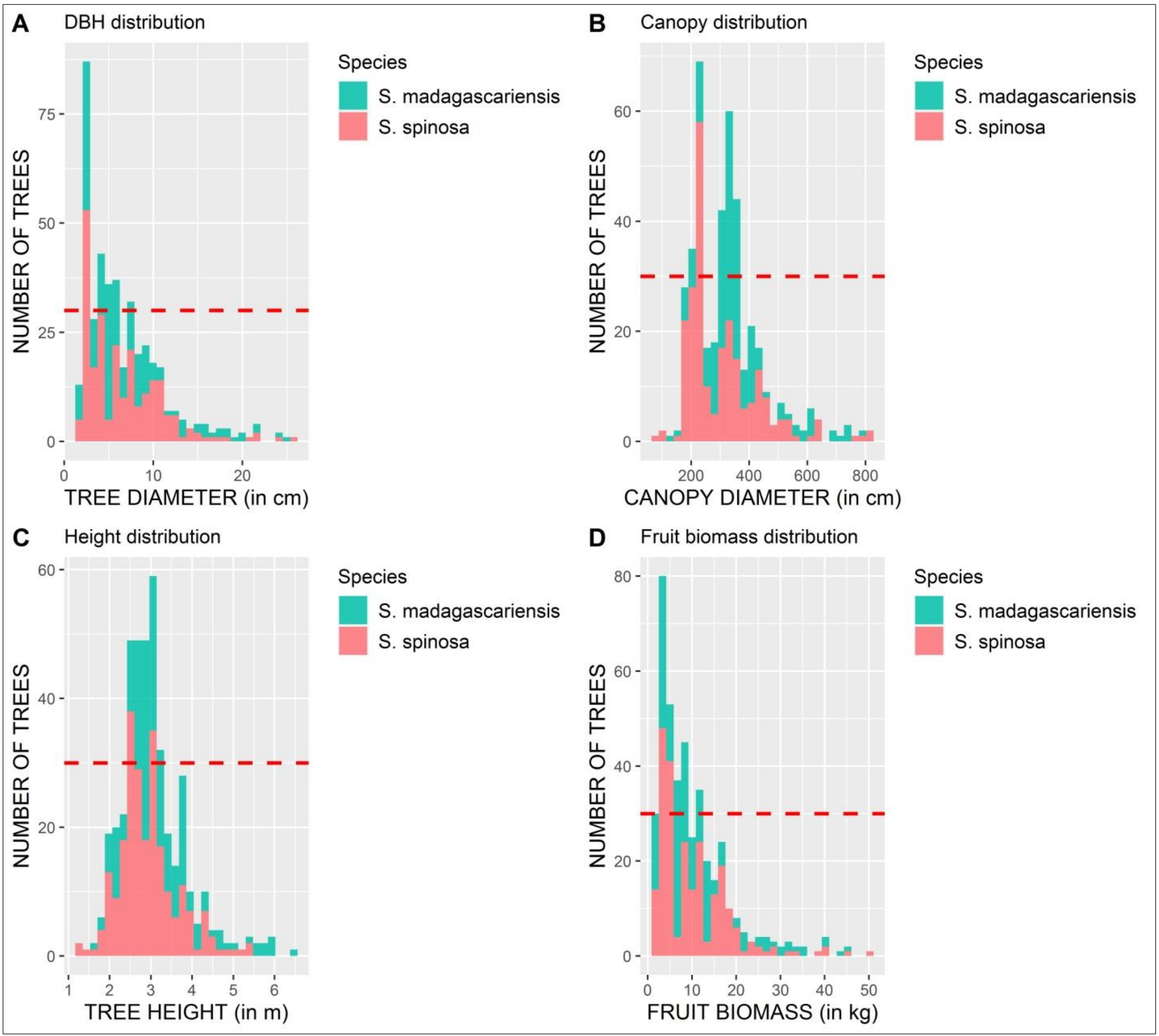
6.5.1. Tree parameters distribution

There was a high concentration of trees with a diameter class between 2 and 6.8 cm. In this diameter class, there were a total of 258 trees which represented 61.4% of all trees measured in this study. There was a noticeable presence of young trees whose diameters ranged between 2 and 3 cm (Chap6-Figure 3A). The second diameter class (DBH = 6.9-11.6 cm) included about 117 trees with an almost uniform distribution. The number of trees in the third (DBH = 11.7-16.5 cm), fourth (DBH = 16.6-21.3 cm) and fifth diameter class (DBH = 21.4-26.1 cm) were very few, making a total of only 45 trees for the three diameter classes (Chap6-Figure 3A). Regarding the distribution of trees according to canopy classes, there were 97 trees whose canopy ranged between 80.4 and 229 cm. This first canopy class covered 23% of the trees concerned in this study. The second canopy class (canopy diameter = 230-377 cm) had the highest number of trees (226 trees), which made 53.8% of total trees. As with the tree diameter classes, the last three canopy diameter classes were made up of very few trees (Chap6-Figure 3B). Among the tree height classes, the second class (tree height = 2.34-3.37 m) had the highest number of trees (253 trees), which accounted for 60.2% of the total trees observed (Chap6-Figure 3C). About 295 trees (representing 70.2% of total trees) had fruit biomasses that ranged between 2.29 and 12 kg (Chap6-Figure 3D).



Chap6-Figure 3: Distribution of the amount of trees of *Strychnos madagascariensis* and *Strychnos spinosa* per classes of tree diameter (A), canopy diameter (B), tree height (C), and fruit biomass (D).

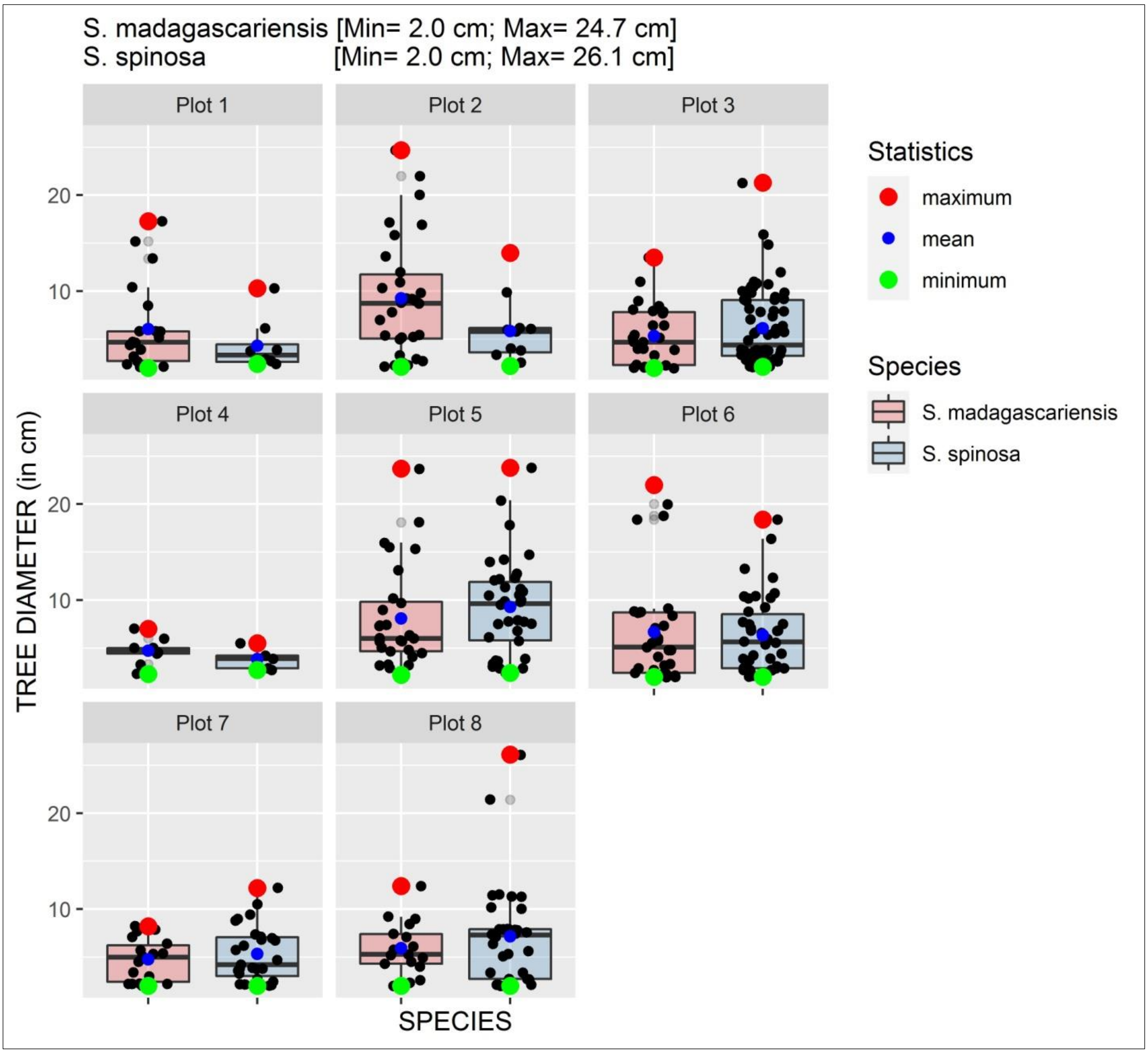
Basing on the distribution of tree parameters by the investigated species, the study shows that the diameter, the canopy, the height, and the fruit biomass of the trees had markedly different distributions (Chap6-Figure 4). Classes with tree distributions greater than 30 were much more often observed with *S. madagascariensis*, particularly for trees whose diameter ranged between 2 and 6.8 cm (Chap6-Figure 4A); canopy between 300 and 400 cm (Chap6-Figure 4B); and whose height ranged between 2.5 and 3.2 m (Chap6-Figure 4C). However, in general, there were more *S. spinosa* trees (56.2%) than there were for *S. madagascariensis* (43.8%).



Chap6-Figure 4: Histogram of frequencies of tree diameter (A), canopy diameter (B), tree height (C), and fruit biomass (D) by *Strychnos* species. The red dotted line represents a frequency level of 30 trees. Bars above the line are considered high frequency.

The tree diameter of *S. madagascariensis* ranged from 2.0 to 24.7 cm while that of *S. spinosa* ranged between 2.0 and 26.1 cm. The mean values of tree diameter per species and per study plots were almost comparable. Chap6-Figure 5 summarizes the dispersion of tree diameter of *S. madagascariensis* and *S. spinosa* per sampled plots. In

Plot 4, the dispersion of tree diameter was very weak (Chap6-Figure 5). This plot was composed of trees with a diameter ranging from 2.0 to only about 7 cm. Apart from Plot 4, all other plots had a wider range of tree diameter.



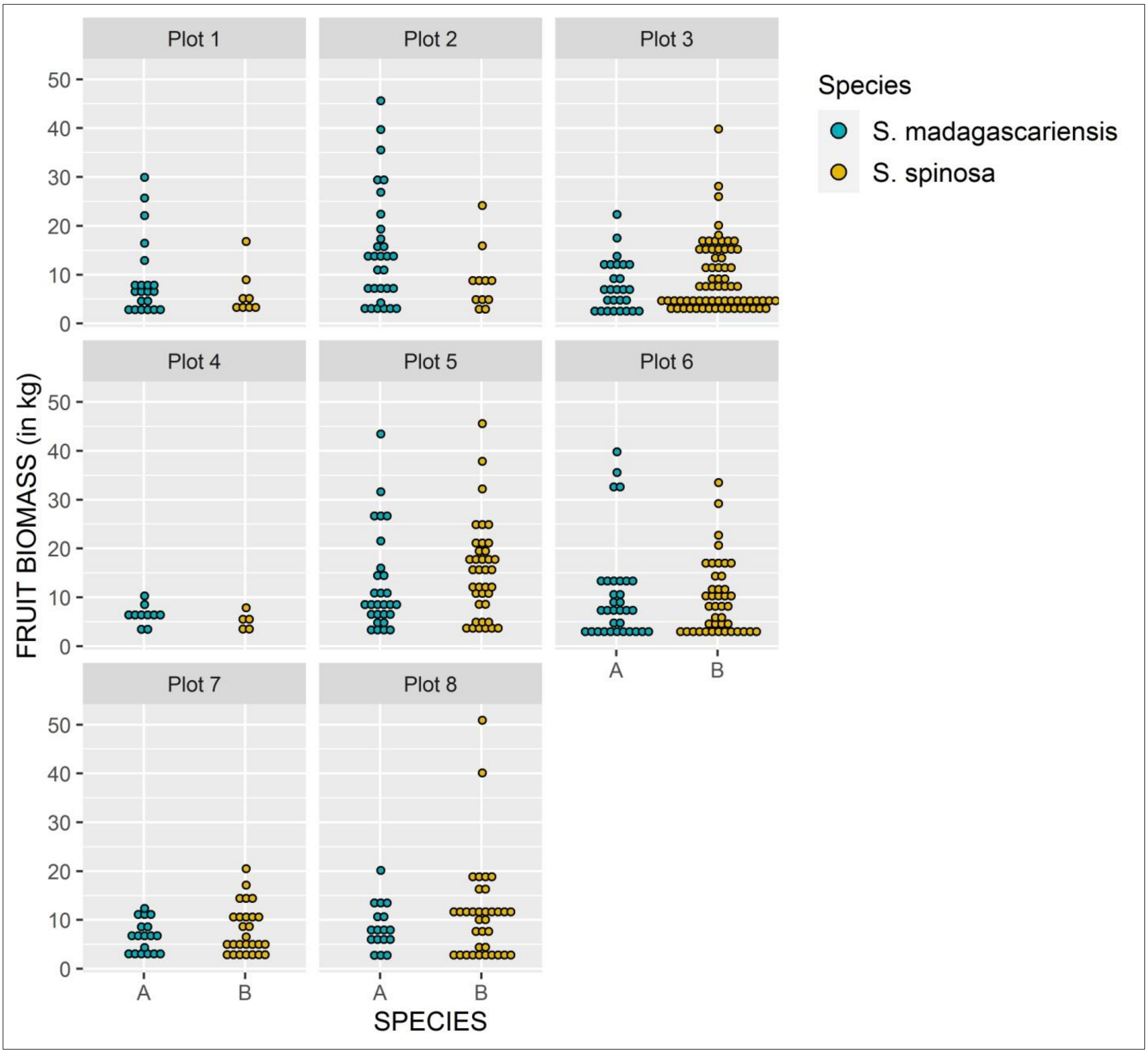
Chap6-Figure 5: Summary of statistical dispersion parameters of the diameter at breast height of the trees of *Strychnos madagascariensis* and *Strychnos spinosa* per sample plot. Each sample plot has an area of 2500 m^2. The overall minimum (Min) and maximum (Max) values of tree diameter are given per species.

6.5.2. Fruit biomass within Plots

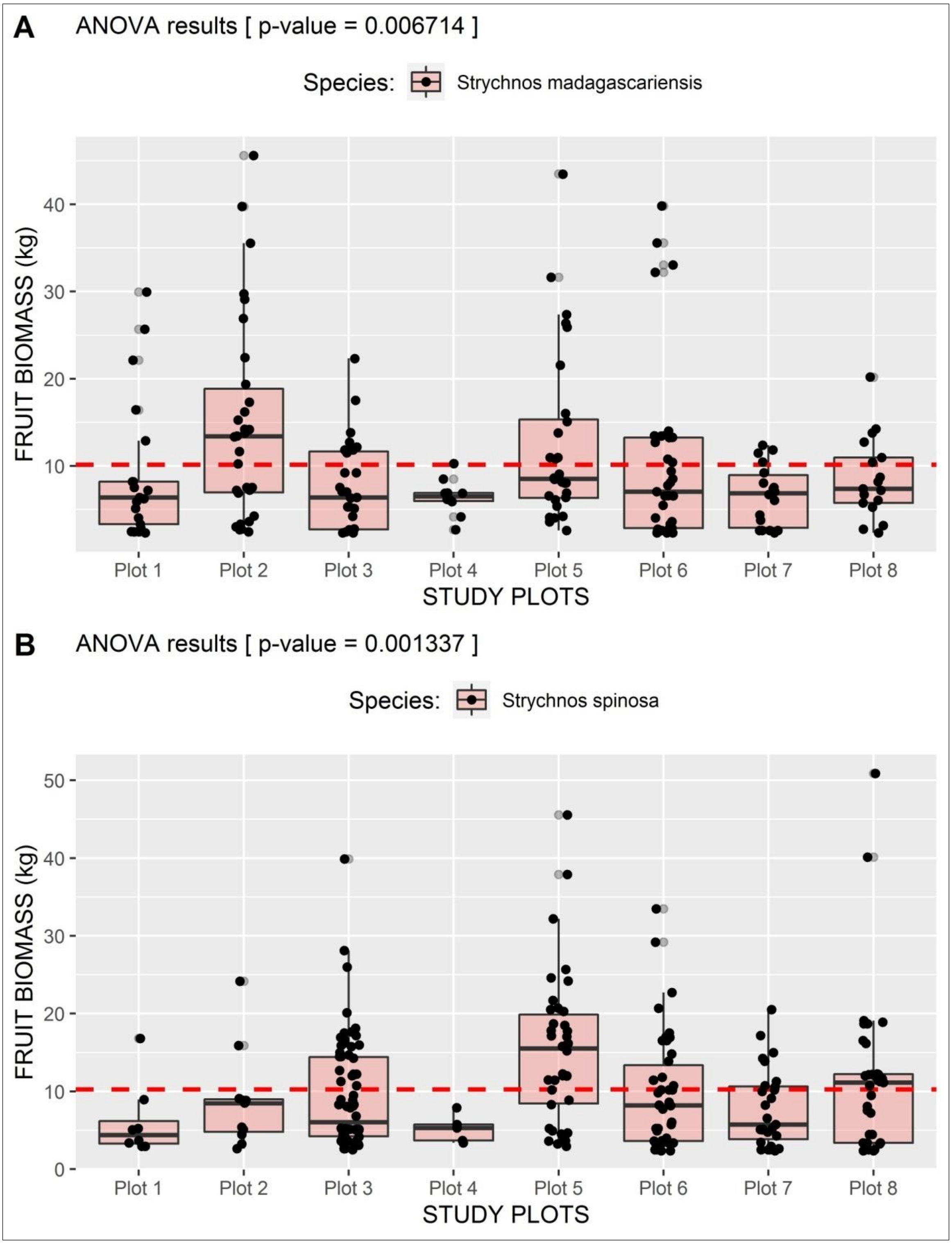
For all the plots and species studied, there was a total of 4294 kg of fruit biomass recorded. *Strychnos spinosa* contributed 56.4% of the total fruit biomass (corresponding to 2423.60 kg) while *S. madagascariensis* contributed 43.6% (1870.40 kg). The mean values of the fruit biomass of the sampled plots were 233.80 kg and 302.95 kg for *S. madagascariensis* and *S. spinosa*, respectively. However, the standard deviations associated with these mean fruit biomasses were relatively large (Chap6-Table 1). In some plots (Plot 1 and Plot 4), the total fruit biomass per species was markedly lower than in others (Chap6-Table 1). The same trend was also observed with the number of trees per species within plots. Plot 3 and Plot 6 had more fruit biomass than the rest of the plots for both species (Chap6-Figure 6). In addition, *S. madagascariensis* fruit biomass was substantially dominant in some plots (Plot 1 and Plot 2) than in others compared to that of *S. spinosa*. The same trend was observed for *S. spinosa*, whose fruit biomass was dominant in Plot 3 and Plot 8 (Chap6-Figure 6). The ANOVA of the fruit biomass data distribution within the plots gave the following values of *p-value* parameter: 0.0067 and 0.0013, respectively for *S. madagascariensis* and *S. spinosa* groups (Chap6-Figure 7).

Chap6-Table 1: Distribution of trees and their fruit biomass in the sample plots of *Strychnos madagascariensis* and *Strychnos spinosa*. Each sample plot has an area of 2500 m^2. Standard deviations are given for mean values.

Sample plots	Number of trees	Fruit biomass (kg)	Number of trees	Fruit biomass (kg)
	Strychnos madagascariensis		*Strychnos spinosa*	
Plot 1	21	190.20	8	49.00
Plot 2	30	446.89	11	96.15
Plot 3	27	206.75	70	655.07
Plot 4	10	64.55	5	25.98
Plot 5	28	354.46	38	578.71
Plot 6	33	342.45	42	409.26
Plot 7	18	119.14	27	211.65
Plot 8	17	146.01	35	397.82
Total	184	1870.40	236	2423.60
Mean	23 ± 8	233.80 ± 133	30 ± 21	302.95 ± 242



Chap6-Figure 6: Dot chart of fruit biomass by *Strychnos* species and per sample plot. Each sample plot has an area of 2500 m^2.



Chap6-Figure 7: Box chart and one-way analysis of variance (ANOVA) of the fruit biomass of *Strychnos madagascariensis* (A) and *Strychnos spinosa* (B) by sample plots. The p-value represents a result parameter of the ANOVA test. The red dotted line indicates the overall mean value of fruit biomass per species. The black dots are single fruit biomass values of a tree and the horizontal black lines inside the boxes are the median values for each group.

6.5.3. Fruit biomass per surface unit

On average, the production capacity of the CPUM in terms of fruit biomass per surface unit was 935.2 ± 532 kg ha^{-1} and 1211.8 ± 971 kg ha^{-1}, respectively for *S. madagascariensis* and *S. spinosa* (Chap6-Table 2). There were large variations in the fruit biomass between the plots. Fruit biomass was lowest in Plot 4′, which had 258.2 kg ha^{-1} of *S. madagascariensis* fruit and 103.92 kg ha^{-1} of *S. spinosa*. The highest fruit biomass for both species was recorded in Plot 5′. In this plot, *S. madagascariensis* and *S. spinosa* had fruit biomass yields of 1417.84 kg ha^{-1} and 2314.84 kg ha^{-1}, respectively.

Chap6-Table 2: The average amount of the fruit biomass of *Strychnos madagascariensis* and *Strychnos spinosa* in the plots converted to surface unit of one hectare each.

Converted plots	Fruit biomass (kg ha^{-1})	
	Strychnos madagascariensis	*Strychnos spinosa*
Plot 1′	760.80	196.00
Plot 2′	1787.56	384.68
Plot 3′	827.00	2620.36
Plot 4′	258.20	103.92
Plot 5′	1417.84	2314.84
Plot 6′	1369.80	1637.04
Plot 7′	476.56	846.60
Plot 8′	584.04	1591.28
Total	7481.60	9694.40
Mean	935.20 ± 532	1211.80 ± 971

6.5.4. Fruit biomass production in the CPUM

The central portions of the Umhlabuyalingana municipality produced in total 13 192.98 tons (t) and 17 095.01 t of fresh fruit biomass for *S. madagascariensis* and *S. spinosa*, respectively. Of the rural area sampled, Enhlambeni contributed the most fruit biomass, with an estimated production of 3571.39 t and 4627.69 t, respectively for *S. madagascariensis* and *S. spinosa*. The rural area that had the least contribution to the fruit biomass was Mabhudu (Chap6-Table 3).

Chap6-Table 3: Estimations of the fresh fruit biomass production in the central portions of the Umhlabuyalingana municipality, located in the Umkhanyakude district of KwaZulu-Natal province, South Africa. Fruit biomass is expressed in ton (t).

Rural cities	Area of measured portions (ha)	Estimated fruit biomass (t)	
		S. madagascariensis	*S. spinosa*
Mlamula	3088.45	2 888.318	3742.583
Mabhudu	672.28	628.716	814.668
Mangwenya	1589.2	1486.219	1925.792
Enhlambeni	3818.86	3571.397	4627.694
Thokazi	2948.24	2757.194	3572.677
Jobe	1990.09	1861.132	2411.591
Total	14107.12	13 192.98	17 095.01

6.6. Discussion

6.6.1. Tree parameters distribution

The diameter of the majority of the trees (61.4%) sampled ranged between 2 and 6.8 cm. There were very few trees in the larger diameter classes. The diameter distribution of the trees had an inverted J-shaped structure (Chap6-Figure 3A). This is a common distribution structure in savannah woodlands (Rudge et al. 2021). According to Savadogo et al. (2007), an inverted J-shaped structure is an indication that the vegetation is dominated by young individuals. Several factors can explain this trend. *Strychnos* species are light-demanding and they tolerate the harsh conditions of summers (Ngadze 2018). At an earlier stage, juvenile individuals face less competition for sunlight as they grow in open stands. This promotes a simultaneous growth of younger trees. Syampungani et al. (2016) also attributed the fast-growing and the dominance of younger trees of miombo woodlands to maximum exposure to sunlight. This explains the inverted J-shaped diameter distribution structure obtained in most field surveys (Savadogo et al. 2007). Recently, Mengich et al. (2020) suggested that the J-shaped diameter distribution structure reflects a regenerating and stable population that is adapted to its site. This view has however been questioned as it is based on an unrealistic biological assumption of equal mortality among size classes (Zimudzi and Chapano 2016). Generally, saplings/juveniles are highly susceptible to bush fires (Werner and Prior 2013). The high abundancy of juvenile plants suggests that there is no regular bush fires that keep the juvenile *S. madagascariensis* and *S. spinosa* in check. Indeed, bushfire has not so far been reported as a major threat in the study area, thus giving saplings a better chance to grow in large numbers (Holdo 2006). In addition, the absence of anthropogenic activities such as slash-and-burn agriculture in the study area can also be one of the reasons for the dominance of juveniles.

The inverted J-shaped distributions were also observed with the tree canopy diameter (Chap6-Figure 3B) and the fruit biomass (Chap6-Figure 3D). However, for the tree canopy, there was poor representation of trees in the first class of canopy diameter (80.4 - 229 cm). This is normal because most of the savannah species do not develop a large canopy until they reach a certain height. With regards to the distribution of fruit biomass, 70.2% of total trees had biomass that ranged between 2.29 to 12 kg (Chap6-Figure 3D). This is linked to the dominance of young trees. Small-sized trees have low fruit biomass. Therefore, their number influences the distribution of the fruit biomass. On the other hand, the distribution structure of trees within height classes was quite different compared to that of the above-mentioned parameters. Chap6-Figure 3C displays a funnel-like distribution of tree height. The literature reports that the tree height distribution can substantially vary depending on the species and the forest stand (Rupšys 2016). However, this distribution is important for the understanding of competition among trees (Rupšys 2016). The suggested explanation for the tree height distribution observed in this study is that when trees exceed 3.37 m, they favour canopy expansion.

Nevertheless, in this study, the distribution of the tree parameters was different depending on the species. The difference was much more related to the positioning of the distribution peaks. For most parameters, the peaks were encountered with *S. madagascariensis* species (Chap6-Figure 4). This means that the growth rate of trees differed between the two species.

6.6.2. Fruit biomass within Plots

This study aimed to evaluate the total production capacity of the CPUM in terms of fruit biomass. To achieve this, several steps were therefore required. Knowing the distribution of fruit biomass in the plots was a crucial step in determining the average fruit biomass production capacity per surface unit of savannah woodlands of the CPUM. There were strong disparities in the distribution of fruit biomass in the study plots. These disparities were observed both at the level of plots and species. The results indicated that Plot 1 and Plot 4 had the lowest fruit biomass while Plot 3 and Plot 6 had the highest fruit biomass (Chap6-Table 1; Chap6-Figure 6). Moreover, there was high dominance of *S. madagascariensis* fruit biomass in Plot 1 and Plot 2 whereas *S. spinosa* fruit biomass dominated in Plot 3 and Plot 8. The ANOVA confirmed that the difference between plots in the distribution of fruit biomass was statistically significant (*p-value* < 0.05). This implied that, at 95% confidence interval, space is a factor that determines the distribution of fruit biomass of *S. madagascariensis* and *S. spinosa*. This, therefore, justifies the high standard deviations observed with the mean fruit biomasses of the plots (Chap6-Table 1). Some studies have proven that factors such as multiple land use and precipitation regime can create severe transitions in the distribution of above-ground biomass (AGB) of trees in savannah woodlands (de Miranda et al. 2014; Amara et al. 2020). Savanna ecosystems are highly dynamic in space and time (Levick et al. 2021). I believe that the same factors mentioned above can also explain the disparities in the distribution of fruit biomass observed in this study. Even if these factors concerned the distribution of AGB of trees, there is however a relationship between dimensions of a tree and its fruit biomass (Peters et al. 1988; Chapman et al. 1992; Akweni et al. 2020).

6.6.3. Fruit biomass per surface unit

Currently, the CPUM has a large expanse of savannah which is protected from anthropogenic impacts. Its wooded areas possess a high diversity of fruit tree species that present a great potential for commercial harvest from the wild. It was observed in this study that the CPUM produced on average 935.2 ± 532 kg ha^{-1} and 1211.8 ± 971 kg ha^{-1} of fruit biomass, respectively for *S. madagascariensis* and *S. spinosa*. These findings are important in estimating fruit biomass production on the scale of a biome. Usually, in rural areas, local communities do not venture into commercial harvesting of fruits from the wild because of many reasons. Among the reasons, we can mention the difficulty to predict fruit biomass production from tree dimensions and the lack of knowledge on the economic value of their woodlands. This discourages entrepreneurship involving the fruits. The current study and that of Akweni et al. (2020) have pioneered fruit biomass prediction and production potentials of woodlands based on tree dimensions. Unfortunately, these two studies focused only on *S. madagascariensis* and *S. spinosa*. Other valuable fruit tree species need to be considered in future studies.

6.6.4. Fruit biomass production in the CPUM

Umhlabuyalingana municipality is one of the poorest rural areas of South Africa. A large part of the municipality is still underdeveloped. The municipality has a large area of natural vegetation that contains a high number of fruit tree species that could be exploited for poverty alleviation. The *Strychnos* species are among the most widespread and appreciated wild fruit trees in the municipality (Boon 2010; Nkosi et al. 2020), and have potential for commercialization. However, so far, the fruit biomass production potential of *Strychnos* species is currently not known. This study estimated the fruit biomass production of *S. madagascariensis* and *S. spinosa* in the CPUM. It was revealed that the CPUM, covering 14107.12 ha, had the potential to produce 13192.98 t and 17095.01 t of fresh fruit biomass of *S. madagascariensis* and *S. spinosa*, respectively (Chap6-Table 3). These results sufficiently prove that the CPUM possess a large potential for the production of fruit biomass. If we consider the rounded average weight of the fruits of *S. madagascariensis* and *S. spinosa* at 350 g and 400 g (Akweni et al. 2020), the CPUM would respectively yield about 37 and 42 million fruits for both species per year. In addition, based on the price of *Strychnos* sp. in rural markets of Namibia (Elago and Tjaveondja 2015), namely 0.06 USD (US Dollars) per fruit; the CPUM can potentially generate an annual income of 2.2 and 2.5 million of USD for *S. madagascariensis* and *S. spinosa*, respectively. In other words, commercial harvesting of the fruits of both species from the wild can generate income and create sustainable employment in the Umhlabuyalingana municipality. This study supports that, through commercial harvesting of the fruits from the wild, the CPUM can substantially boost household economies. Ngadze et al. (2017), Koffi et al. (2020), and Nkosi et al. (2020) have also mentioned that the commercial harvesting of fruits from the wild can generate revenues and enhance food security.

Nevertheless, the above extrapolations remain theoretical. In reality, the harvestable fruit yield can be much lower than what is reported in this study for several reasons, including the need to retain some fruits for natural regeneration; the loss of fruits due to frugivore species; the damage to some fruits from pests and diseases; and the loss of fruits on the ground due to wildfires. This implies that to obtain a realistic harvestable yield, a correction factor needs to be applied to the global yield presented in this study. Further studies are necessary to address such corrections and to evaluate the economic feasibility of projects based on the harvesting and processing of the fruits. In addition, this study did not consider the inter-annual variation of fruit yield. The fruit-based equations used in this study to derive the fruit biomass of trees were calibrated from data of one fruiting season (Akweni et al. 2020) whereas fruit yield can vary a lot from one season to another.

6.7. Conclusion

This study investigated *S. madagascariensis* and *S. spinosa* fruit biomass production in the CPUM. Results from the present study point to a huge untapped potential for commercialization of *S. madagascariensis* and *S. spinosa* in the Umhlabuyalingana municipality. The two species are present in fairly large stable populations with good recruitment and produce high fruit biomass necessary for the uptake of business ventures to exploit them commercially. Wild exploitation of these resources presents opportunities for development of the KwaZulu-Natal province in general and the Umhlabuyalingana municipality in particular.

CHAPTER 7: FRUIT ALLOMETRY OF *TRICHILIA EMETICA*

7.1. Full title

Predicting the number of fruits and the seed biomass of *Trichilia emetica* (Vahl.) in the eastern coastal region of South Africa.

7.2. Abstract

Trichilia emetica is a coastal fruit tree species from sub-Saharan Africa that has a potential for commercial harvest for its edible and useful seed oils. However, the prediction of its fruit and seed yields is necessary to plan a profitable harvest. The study reported in this chapter aims to calibrate allometric equations that predict the amount of fruits and the biomass of seeds of *T. emetica*. A total of 35 trees were selected based on seven classes of the diameter at breast height (DBH) in the Umkhanyakude district. The trees were measured during fruit maturation period. The measurements included the DBH, the canopy diameter, and the total height. Fruits were counted on each tree using randomized branch sampling technique. Twelve fruits were harvested per tree and were brought to the laboratory for the determination of biomass. Six allometric models were identified and fitted to the data using ordinary least squares method. The Akaike information criterion (AIC) was used to select the best-fit models. The results suggested that simple linear models, basing solely on DBH (in cm), were the best predictors of both the number of fruits on the trees (NF) and the fresh seed biomass (SB; in kg) of *T. emetica*. The exponential forms of the best-fit general models were: (1) NF = 375.364 × $DBH^{1.009}$; and (2) SB = 1.858 × $DBH^{1.009}$. The prediction tests of these models indicated that the errors were large when predicting the fruit number and the seed biomass of smaller trees (DBH ≤ 20 cm) and bigger trees (DBH ≥ 30 cm). For medium-size trees (20 cm < DBH < 30 cm), the error was small. On the other hand, tree size category models developed in this study improved statistically the accuracy of predictions. The findings recommend the use of the fitted tree size category equations.

Keywords: fruit number; seed biomass; prediction; allometry; *Trichilia emetica*.

7.3. Introduction

Trichilia emetica, also known as Natal mahogany (Komane et al. 2011), is an evergreen fruit tree species widely distributed throughout sub-Saharan Africa and naturally occurs in riverine forests (Bussmann et al. 2021), coastal areas (Boon 2010; Mucina 2018), and in various types of woodlands. *Trichilia emetica* has two subspecies namely: subsp. *emetica* and subsp. *suberosa* J.J. de Wilde (Malafronte et al. 2013). The subsp. *suberosa* occurs mostly in Senegal and Uganda while the subsp. *emetica* can be found in Eritrea, Ethiopia (Fekadu and Yohannes 2004), and in South Africa (Mucina and Rutherford 2006) where it is locally known as Christmas bells (in English), Umathunzini (in isiZulu), Umkhuhlu (isiXhosa), Nkulu (Xitsonga), and Mutuhu (TshiVenda). *Trichilia emetica* is morphologically similar to *Trichilia dregeana* Sond. These two species are often confused. *Trichilia emetica* is a multi-purpose fruit tree species used by local communities and small-scale traders (Mashile et al. 2018). In southern Africa, the wood of *T. emetica* is the most preferred in wood carving and sometimes it is also used as a fire wood. A decoction of the stem bark is used as a remedy for colds and pneumonia and for a variety of intestinal disorders (Fekadu and Yohannes 2004; Komane et al. 2011; Tsopgni et al. 2019). The fruits of *T. emetica* are used in supplementary diets (Fekadu and Yohannes 2004). They contain black and bright-red seeds which represent an important source of food for local communities (Mashungwa and Mmolotsi 2007). Seeds are soaked in water and the milky soup is eaten with spinach. The seed arils are cooked along with sweet potatoes or squash and the seed cakes serve as organic fertilizers. It is also reported that a pre-treatment of the seeds can yield a biodiesel of good quality (Adinew 2014a).

In addition to being a source of food, the seeds of *T. emetica* yield two kinds of oil namely: (1) Mafura oil (Matakala et al. 2005), which is obtained from the fleshy envelope of seeds and (2) Mafura butter obtained from the kernel. Mafura oil is edible (Adinew 2014b) and is preferred for its particular properties (Khumalo et al. 2002). On the other hand, Mafura butter is not palatable but it is used to manufacture soap and candles (Nchimbi 2020). It is also used in skin care products (Khumalo et al. 2002; Poojary and Passamonti 2020) and in popular medicine (Fekadu and Yohannes 2004). Mafura butter has long been commercialized in eastern African countries. Between the years 2000 and 2004, Mozambique was the main exporter with an estimated production of 100–300 tons per year (Mashungwa and Mmolotsi 2007). To date, the oil is still extracted from the seeds using traditional methods and its commercialization continues on a small scale. The commercial potential of *T. emetica* has not yet been fully exploited and the agro-industrial development of its oil requires an urgent attention (Grundy and Campbell 1993; Amália and Samuel 2016). The envelope of the seeds can yield 48.4−50.2% of oil (Nchimbi 2020). This is higher than many reported commercial plant seed oils (Adinew 2014b). Besides, the characteristics of the seed oil of *T. emetica* are comparable to that of palm oil and olive oil (Amália and Samuel 2016), making it a potential addition to the current cooking oils market. Thus, campaigns of commercial harvesting of the fruits/seeds of *T. emetica* can create jobs and alleviate poverty. For example, the trade of Mafura butter in cosmetic industries can be a source of income for the local community (Vermaak et al. 2011; Adinew 2015; Poojary and Passamonti 2020). This can boost household economies particularly in rural areas. In the province of KwaZulu-Natal (in South Africa), specifically in the districts of Big 5 Hlabisa and UMkhanyakude, *T. emetica* is abundantly spread along road sides and parking lots. This distribution is strategic in the advent of planning a commercial harvest of the fruits or seeds. *Trichilia emetica* can also be useful in agroforestry systems (Matakala et al. 2005) because it furnishes diverse services such as shade and erosion control. Under optimal conditions (Sershen et al. 2014), *T. emetica* can grow up to 2 m/year (Mashungwa and Mmolotsi 2007) and can attain productive size within a short period. It also has potential to produce medicines (Diallo et al. 2003; Germano et al. 2005; Komane et al. 2011) and pesticides (Lovang and Wildt-Persson 1998).

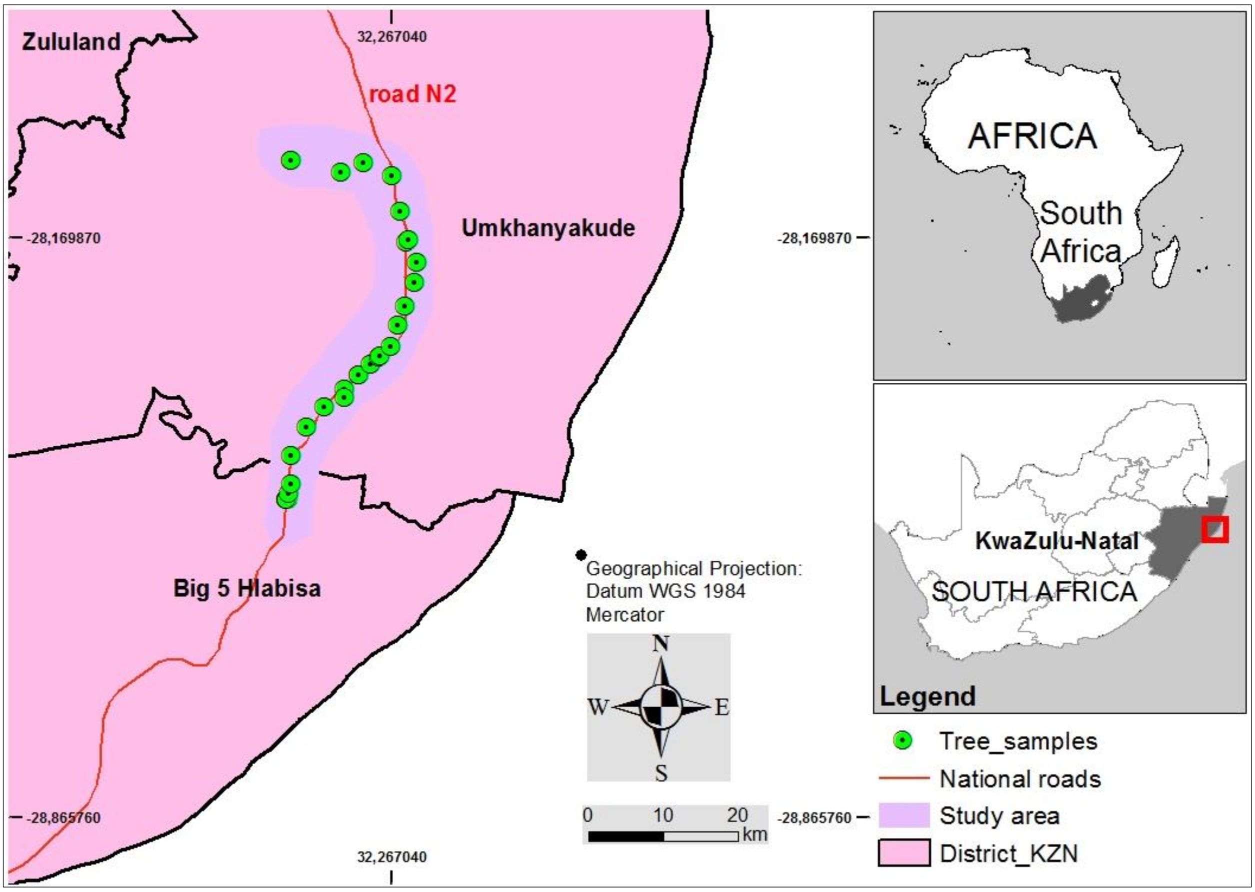
Currently, wild *T. emetica* and its by-products are not involved in agro-industrial and agribusiness processing as this requires a prior assessment of the available plant resources. This assessment involves the determination of the amount of trees and also the prediction of their biomass production capacity. Biomass of trees refers to the weight of all organic matter (Focardi 2008; Houghton 2008; Basu 2018; Edomah 2018). Its prediction is estimated by the use of allometric equations (Chave et al. 2005; Mensah et al. 2018). The equations used for this purpose are derived based on the diameter at breast height (DBH) and the height of trees (Maniatis et al. 2011; Mensah et al. 2017). There are several types of allometric equations which are classified according to the type of vegetation (Fayolle et al. 2013a), the area (Djomo et al. 2010), the species (Ebuy et al. 2011; Daba and Soromessa 2019) or the compartment of the tree whose biomass is predicted (Fortier et al. 2017). With regards to compartment allometry, there exist allometric equations that only predict the biomass of the root (Kuyah et al. 2012b; Mugasha et al. 2013), the stem (Fortier et al. 2017), the branches (Kaitaniemi et al. 2020), the leaves (Lehtonen 2005; Socha and Wezyk 2007) or the fruits (Peters et al. 1988; Akweni et al. 2020) of a tree or a forest stand. Fruit-based allometric equations for the prediction of fruit and seed yield are not common in the literature. Only recently have Akweni et al. (2020) pioneered the derivation of fruit-based allometric equations for *Strychnos* species in KwaZulu-Natal namely: *Strychnos madagascariensis* (Poir.) and *Strychnos spinosa* (Lam.).

Although allometric equations that enable the prediction of the biomass of *T. emetica* exist (Mensah et al. 2017), they are unfortunately restricted to the prediction of the total above-ground biomass. There is therefore a need to develop allometric equations for deriving the portion of the biomass allocated to the fruits and seeds. The study reported in this chapter aims to develop fruit-based allometric equations that will enable the prediction of the number of fruits and the seed biomass of *T. emetica* with the intention of facilitating the preparation of its commercial harvest in UMkhanyakude district.

7.4. Materials and methods

7.4.1. Study area

This study was conducted in UMkhanyakude district in the northern coastal region of the province of KwaZulu-Natal, in South Africa (Chap7-Figure 1). The study site covers an area of 648.86 km² stretching from the north of the municipality of Mfolozi (in the district of Big 5 Hlabisa) to the northwest of the municipality of Mtubatuba. The study area is 66 m above sea level and the climate is subtropical with an average annual temperature of 21.8 °C and an annual rainfall of 901 mm. Rainfall is predominant during summer. The UMkhanyakude area is mainly covered by wooded grasslands (Jewitt 2018) which fall within the coastal Thornveld vegetation type (Morgenthal et al. 2006).



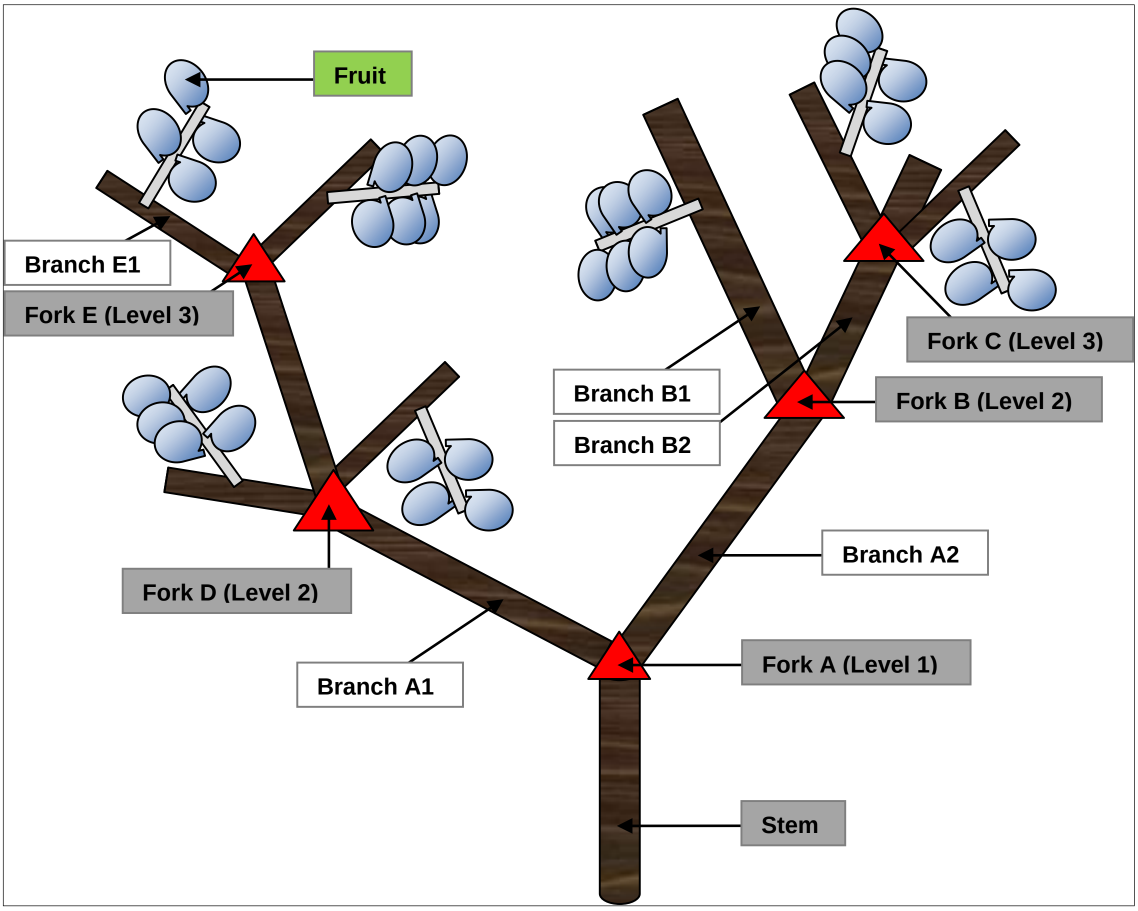
Chap7-Figure 1: Location map of the study area and the harvested trees of *Trichilia emetica* in the province of KwaZulu-Natal, South Africa.

7.4.2. Tree sampling and measurement techniques

A total of 35 trees of *T. emetica* were sampled along the sides of the N2 road (Chap7-Figure 1) over a stretch of 60.5 km within the study area. The trees were selected based on the following classes of the diameter at breast height (DBH; at 1.3 m from the ground): (1) 5 – 10.9 cm; (2) 11 – 15.9 cm; (3) 16 – 20.9 cm; (4) 21 – 25.9 cm; (5) 26 – 30.9 cm; (6) 31 – 35.9 cm; and (7) 36 – 40.9 cm. Each DBH class was represented by five trees. The selection and the measurement of the trees were done gradually according to a south-north gradient of the road. The tree sampling was done along the road because in KwaZulu-Natal, *T. emetica* is spread in large numbers along the road sides and at homesteads. The trees were measured during fruit maturation period. The tree measurements included the DBH, the canopy (or crown) diameter, the total height, the number of fruiting branches, and the geographical coordinates. The DBH, the canopy diameter, and the height of trees were measured using measuring tapes.

7.4.3. Fruit count and seed biomass estimates

Fruits were counted on each tree using a randomized branch sampling technique. This involved the identification and the counting of fruiting branches following a level of branch bifurcation (or fork) as presented in the diagram of Chap7-Figure 2. For smaller trees (DBH ≤ 20 cm; Chap7-Figure 3A), fruiting branches were considered at fork level 1 or 2 whereas for bigger trees (DBH > 20 cm) fruiting branches were considered at fork level 3 or 4. Once fruiting branches were identified, fruits were counted on two randomly selected branches and the average number of fruits was determined. This average was then multiplied by the total number of fruiting branches to generate an estimate of the total number of fruits of the tree (Jessen 1955; Pearce and Holland 1957). Twelve fruits were harvested per tree and were brought to the laboratory for biomass measurements (Chap7-Figure 3B). The measurements were based on the determination of the fruit fresh biomass, the seed fresh biomass (Chap7-Figure 3C), and the number of seeds inside the fruits. The seeds were weighed in groups of six and then individually using a precision scale of 0.01 g (Chap7-Figure 3D).



Chap7-Figure 2: Diagram describing the randomized branch sampling technique for fruit count on a tree of *Trichilia emetica*. In this example, Fork A (Level 1) has two fruiting branches (Branch A1 and Branch A2) that respectively bear 19 and 15 fruits. If Fork A had more than two fruiting branches, this technique suggests that the total number of fruits on a tree would be obtained by multiplying the average of two branches (randomly selected) by the total number of branches. The same technique can be applied at fork level 2 or 3 in the case fruits are borne in peripheral branches.

Chap7-Figure 3: Illustration of the tree (A), fruit (B), and seeds (C, D) of *Trichilia emetica*.

7.4.4. Statistical analysis

The average number of seeds (contained inside the fruits) was multiplied by the estimated total number of fruits of a tree to obtain the total number of seeds of that tree. Thereafter, the total number of seeds of a tree was multiplied by the mean biomass of a single seed to generate the total biomass of the seeds of that tree. These calculations were performed for each tree sampled in this study. The data were encoded in an Excel spreadsheet and analyzed with the R-software (R DEVELOPMENT CORE TEAM, 2018). Regression analysis was performed on data to calibrate prediction equations. Regression analysis was carried out in four stages namely: (1) data dispersion and description, (2) graphic exploration, (3) fitting of models, and (4) selection of models. Dispersion analysis was conducted to assess the scattering of data around the mean and the median values. Graphic exploration was used along with the correlation tests to identify the forms of the allometric models that were appropriate to describe the data. A total of six models were identified and fitted to the data (Chap7-Table 1). The fitting of the coefficients of the models was done using the ordinary least squares (OLS) method (Picard et al. 2012). Only coefficients that were statistically significant at 95% confidence interval were considered. The Akaike information criterion (AIC; Akaike 1974) and the coefficient of determination (R^2) were used to select the best-fit models. A correction factor (CF; Duan 1983) was applied to the selected models after converting their logarithmic expressions into exponential forms. The GGPLOT2 package of Wickham (2016) was used to present the prediction curves of the selected models.

The AIC (Chap7-Equation 1), the CF (Chap7-Equation 2), and the residual standard error (RSE; Chap7-Equation 3) were calculated using the following formulas:

$$AIC = -2 \log (L) + 2q \quad \text{(Chap7-Equation 1)}$$

$$CF = (RSE^2) / 2 \quad \text{(Chap7-Equation 2)}$$

$$RSE = \sqrt{\frac{\sum(x_i - \overline{x})^2}{n-1}} \quad \text{(Chap7-Equation 3)}$$

where “log” is a natural logarithmic function, the term L represents the likelihood of the fitted models, the term q denotes the number of estimated parameters of the models, and RSE is the residual standard error. The symbols x_i, $\overline{x}$, and n represent a random value of seed biomass or fruit count in the dataset [Dataset 1: in supplementary material], the mean value of the considered variable, and the total number of sampled trees, respectively.

Models were developed at species level (general model) and at tree size category level (tree size models). Tree size category was defined based on the properties of the RSE of general model and included: small trees (DBH ≤ 20 cm), medium trees (20 cm < DBH < 30 cm), and big trees (DBH ≥ 30 cm). For both levels, prediction tests were performed to evaluate the difference between the measured and the predicted values of number of fruits and seed biomass. Prediction tests were done using the Student test.

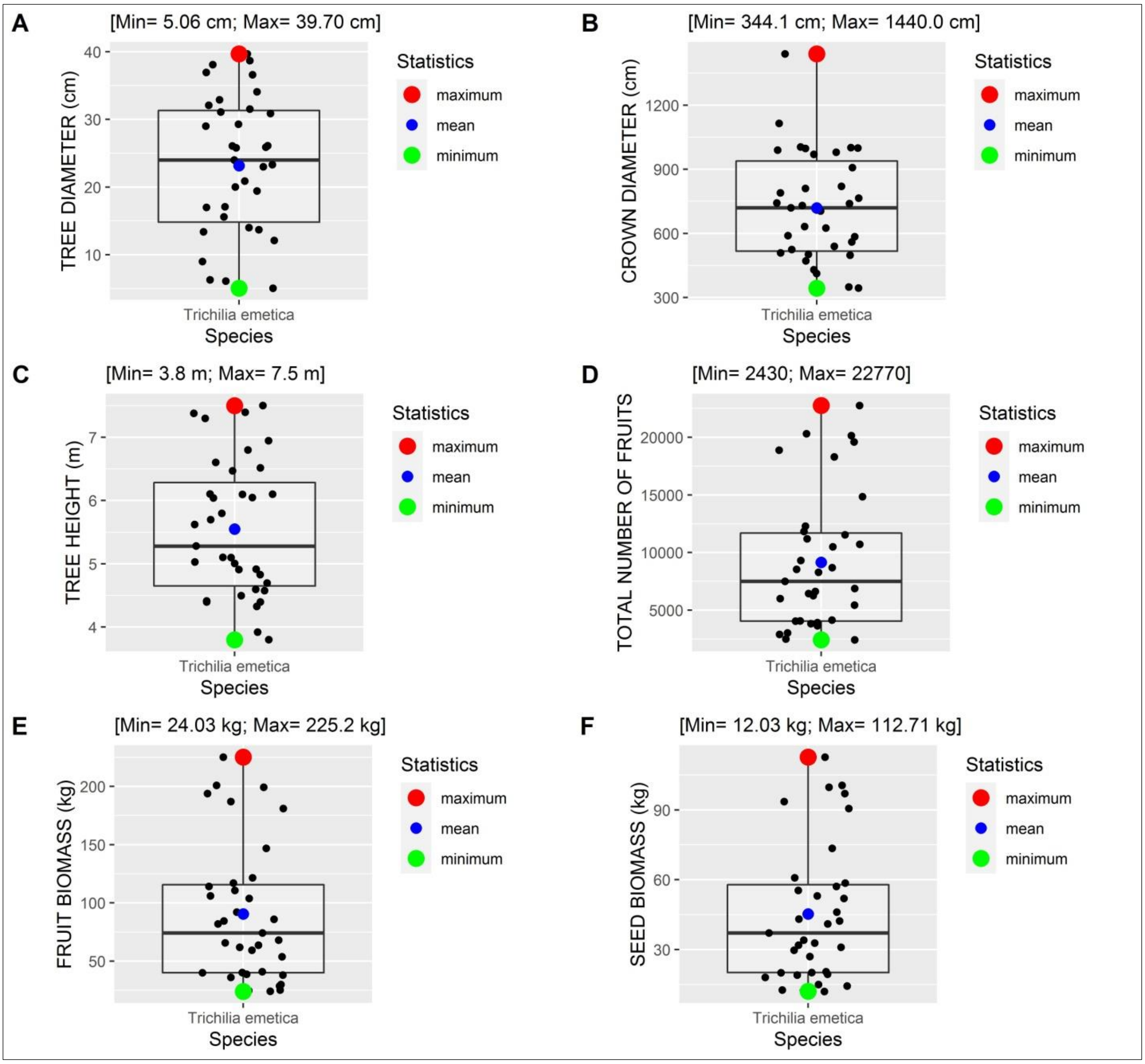
Chap7-Table 1: Allometric models linking the number of fruits (*NF*) and the biomass of the seeds (*SB*, in kg) to the diameter at breast height (*DBH*, in cm), to the tree canopy diameter (*Dc*, in cm), and to the tree height (*H*, in m) of *Trichilia emetica*. The coefficients "a_0, a_1, a_2" are parameters to be estimated by a natural logarithmic function (log) where ε represents the residual error.

Model	Equation
Simple regression	
Model 1	$\log(NF) = a_0 + a_1 \log(DBH) + \varepsilon$ $\log(SB) = a_0 + a_1 \log(DBH) + \varepsilon$
Model 2	$\log(NF) = a_0 + a_1 \log(Dc) + \varepsilon$ $\log(SB) = a_0 + a_1 \log(Dc) + \varepsilon$
Model 3	$\log(NF) = a_0 + a_1 \log(H) + \varepsilon$ $\log(SB) = a_0 + a_1 \log(H) + \varepsilon$
Multiple regression	
Model 4	$\log(NF) = a_0 + a_1 \log(DBH) + a_2 \log(H) + \varepsilon$ $\log(SB) = a_0 + a_1 \log(DBH) + a_2 \log(H) + \varepsilon$
Model 5	$\log(NF) = a_0 + a_1 \log(Dc) + a_2 \log(H) + \varepsilon$ $\log(SB) = a_0 + a_1 \log(Dc) + a_2 \log(H) + \varepsilon$
Model 6	$\log(NF) = a_0 + a_1 \log(DBH) + a_2 \log(Dc) + \varepsilon$ $\log(SB) = a_0 + a_1 \log(DBH) + a_2 \log(Dc) + \varepsilon$

7.5. Results

7.5.1. Description of dendrometric data

The DBH of trees varied between 5 cm and 39.7 cm with a mean value of 23.1 cm whereas the crown diameter ranged from 344.1 cm to 1440 cm with a mean value of 718.6 cm. The lowest and the highest height of trees were 3.8 m and 7.5 m, respectively. The trees bore a maximum of 22770 fruits and a minimum of 2430 fruits. Fresh biomass of fruits attached on trees varied between 24 kg and 225.2 kg. The seed biomass varied between 12 kg and 112.7 kg (Chap7-Figure 4). The biomass of a single fruit of *Trichilia emetica* varied between 6.8 g and 13.2 g with an average of 9.8 g. There were constantly six seeds inside each fruit whose biomass extended from 4 g to 5.8 g. A single seed weighed on average 0.8 g with a small standard variation of 0.07 g (Chap7-Table 2).



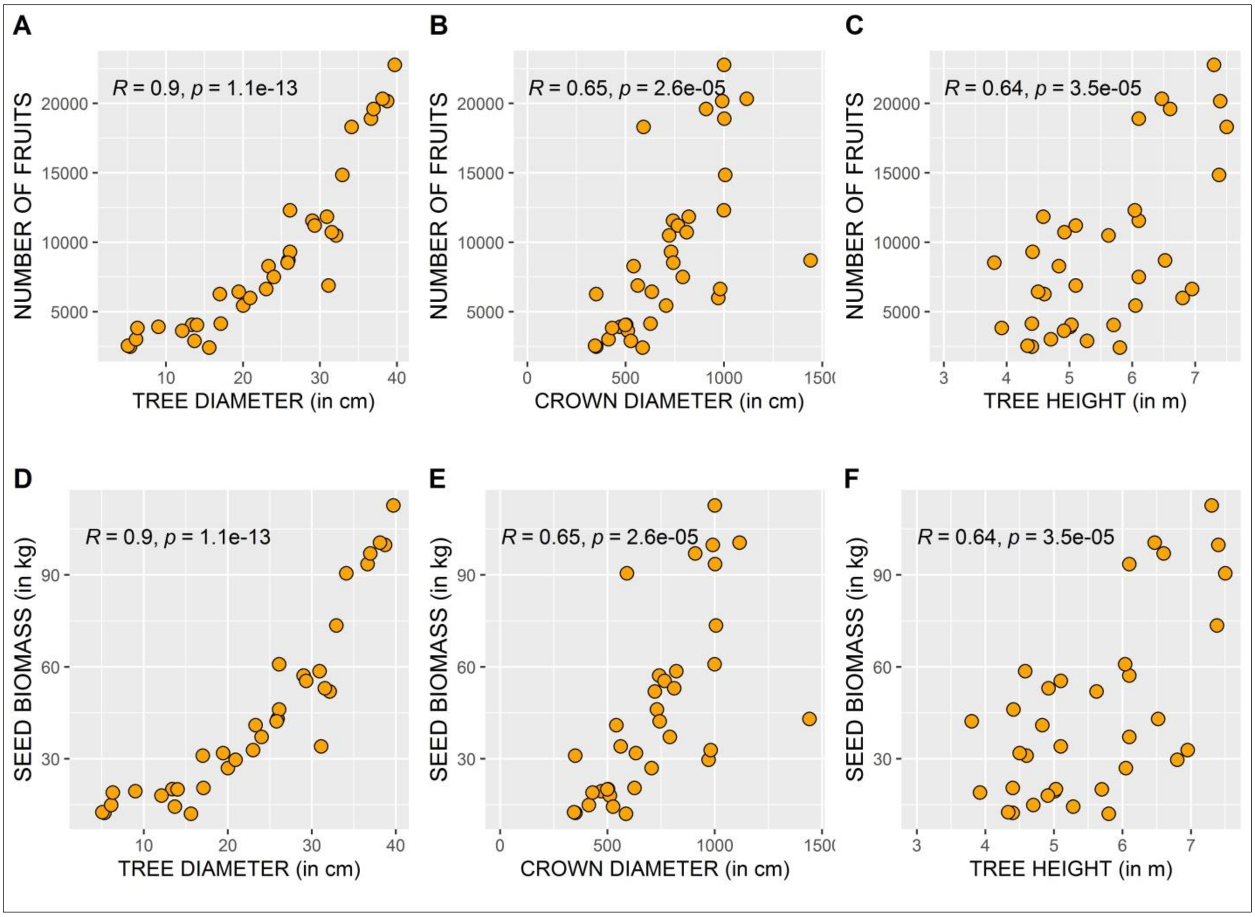
Chap7-Figure 4: Dispersion parameters of tree diameter (A), crown diameter (B), tree height (C), number of fruits (D), fruit biomass (E), and seed biomass (F) of the harvested trees of Trichilia emetica.

Chap7-Table 2: Biomass characteristics of the fruit and seeds of *Trichilia emetica*. The standard deviations are given for global mean values. Each sample group is composed of 12 fruits randomly harvested from 12 trees.

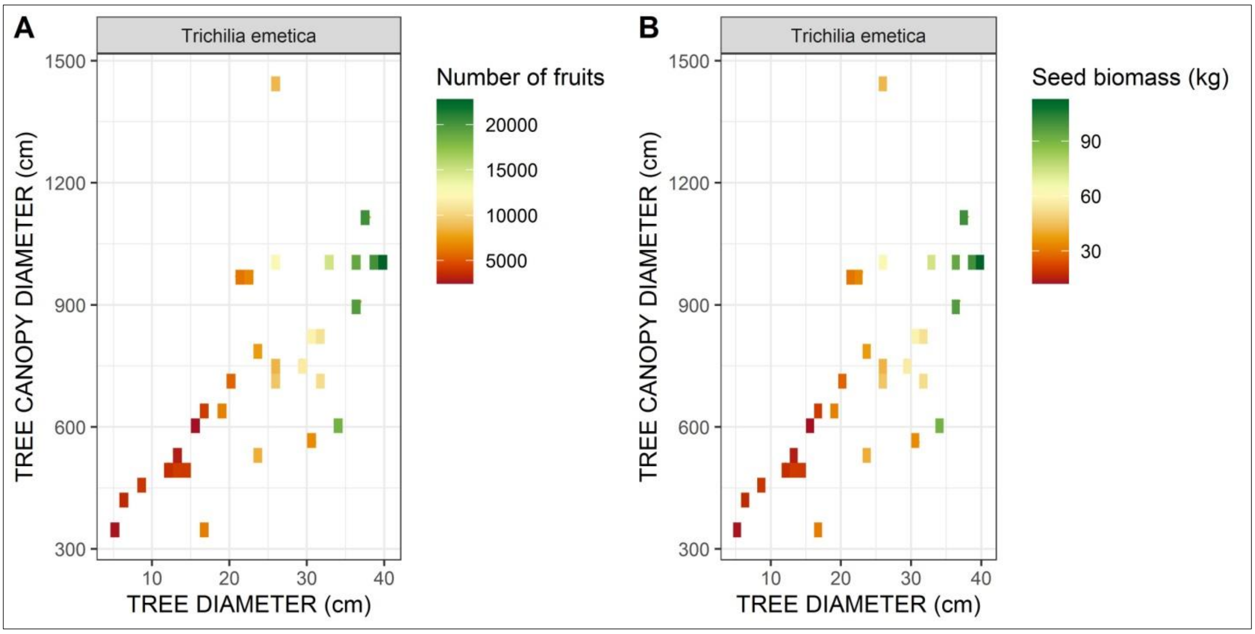
Fruit samples	Average fruit biomass (g)	Average number of seeds per fruit	Average seed biomass per fruit (g)	Average biomass of a single seed (g)
Group 1	12.01	6	5.82	0.97
Group 2	11.75	6	5.34	0.89
Group 3	7.93	6	4.91	0.82
Group 4	9.98	6	4.70	0.78
Group 5	9.80	6	5.01	0.84
Group 6	8.84	6	5.60	0.93
Group 7	13.24	6	4.59	0.77
Group 8	8.20	6	4.42	0.74
Group 9	8.00	6	4.46	0.74
Group 10	6.84	6	4.00	0.80
Group 11	11.88	6	5.51	0.92
Group 12	10.21	6	5.01	0.84
Global mean	**9.89 ± 1.99**	**6 ± 0**	**4.95 ± 0.54**	**0.84 ± 0.07**

7.5.2. Graphic exploration of dendrometric parameters

DBH had a linear dependence with the number of fruits on the trees and they were both strongly correlated by a correlation factor of 0.9 (Chap7-Figure 5A). The crown diameter also had a linear dependence with the number of fruits on the trees but they were linked by a correlation factor of 0.65 (Chap7-Figure 5B). However, the relationship between the height of the trees and the number of fruits on the trees had an irregular distribution and the lowest correlation factor (r = 0.64; Chap7-Figure 5C). The linearity of point clouds was not visibly obvious. Similarly to the number of fruits, the linear dependence of point clouds and the correlation factor linking the seed biomass to the DBH (Chap7-Figure 5D), to the crown diameter (Chap7-Figure 5E), and to the tree height (Chap7-Figure 5F) were decreasing, respectively. Tree parameters (DBH, crown diameter, and height) did not influence the number of fruiting branches (data not shown). However, when plotted together, DBH and crown diameter linearly influenced the gradient of number of fruits (Chap7-Figure 6A) and seed biomass (Chap7-Figure 6B).



Chap7-Figure 5: Graphic exploration of the relationship between the number of fruits and the tree parameters (A, B, C) at one hand; and the relationship between the seed biomass and the tree parameters (D, E, F) of *Trichilia emetica* on the other hand. The correlation coefficient (R) is given for each graph.



Chap7-Figure 6: Relationship between the tree diameter and the tree canopy diameter of *Trichilia emetica* by gradients of number of fruits (A) and seed biomass (B).

7.5.3. Fruit count and seed biomass prediction models

Model 1, linking the number of fruits on the trees and the seed biomass to the diameter at breast height of the trees, had the best fit. The highest value of the coefficient of determination ($R^2 = 0.78$) was observed in Model 1 for both the fruit count and the seed biomass equations. In addition, Model 1 had the lowest value of the Akaike information criteria (AIC = 23.58). Model 2 and Model 3, involving the crown diameter and the height of the trees, did not improve the quality of the fits (Chap7-Table 3). Their fitted coefficients were not statistically significant at the considered confidence interval. Multiple regression models (Model 4; Model 5; Model 6) that involved three variables were not satisfactory in terms of their fitted coefficients. However, Model 4 was potentially the second best model, after Model 1, as it improved the value of the coefficient of determination ($R^2 = 0.77$) and the AIC (AIC = 24.78). After applying the correction factors to the logarithmic expressions of the models, the fitted exponential forms of Model 1 were as follows:

$NF = 375.364 \times DBH^{1.009}$ (Chap7-Equation 4)

$SB = 1.858 \times DBH^{1.009}$ (Chap7-Equation 5)

where NF represents the number of fruits on the trees, SB is the seed biomass (in kg), and DBH is the diameter at breast height of the trees (in cm). Chap7-Figure 7 displays the prediction curves of these general models (fitted at species level). For both curves, the standard errors were relatively large for smaller trees (DBH ≤ 20 cm) and for bigger trees (DBH ≥ 30 cm). Medium-size trees (20 cm < DBH < 30 cm) had smaller standard deviations. Based on these demarcations, tree size category models were also fitted to the data. The exponential expressions of small trees model (Chap7-Equation 6; Chap7-Equation 7), medium trees model (Chap7-Equation 8; Chap7-Equation 9), and big trees model (Chap7-Equation 10; Chap7-Equation 11) were:

$NF = 1409.728 \times DBH^{0.419}$ (Chap7-Equation 6)

$SB = 6.978 \times DBH^{0.419}$ (Chap7-Equation 7)

$NF = 13.416 \times DBH^{2.011}$ (Chap7-Equation 8)

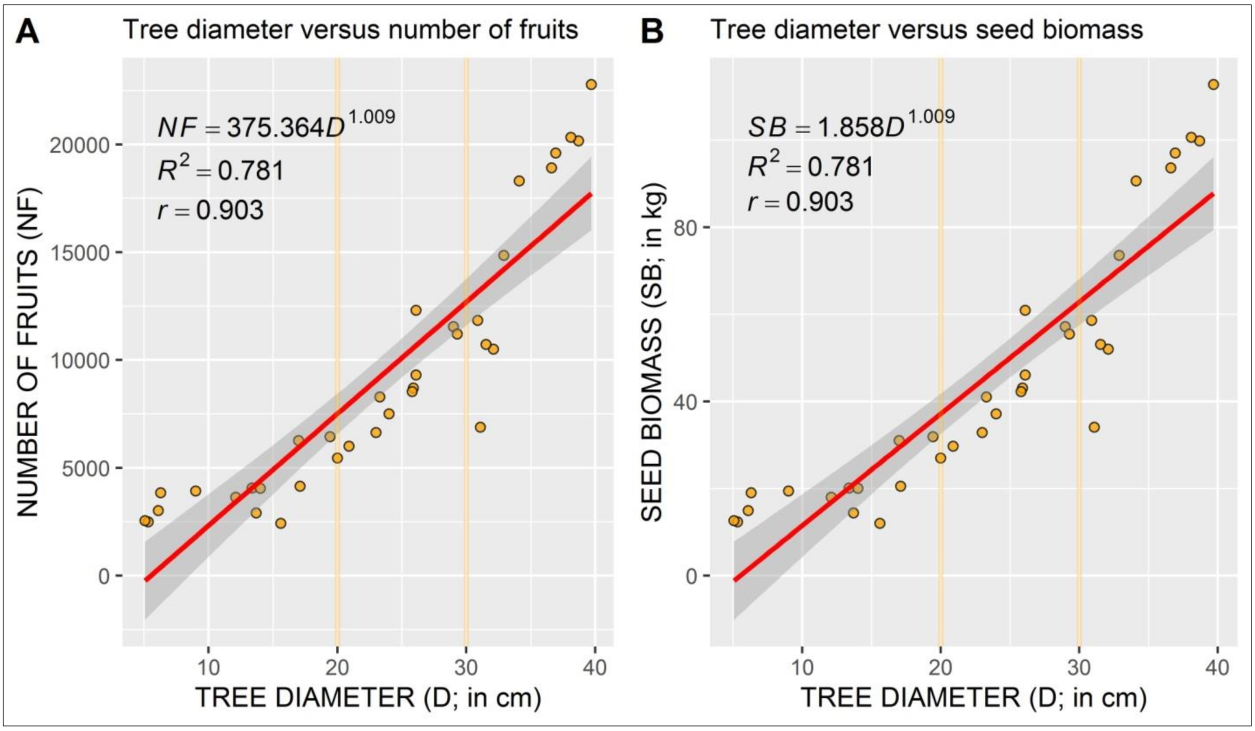
$SB = 0.066 \times DBH^{2.011}$ (Chap7-Equation 9)

$NF = 0.056 \times DBH^{3.53}$ (Chap7-Equation 10)

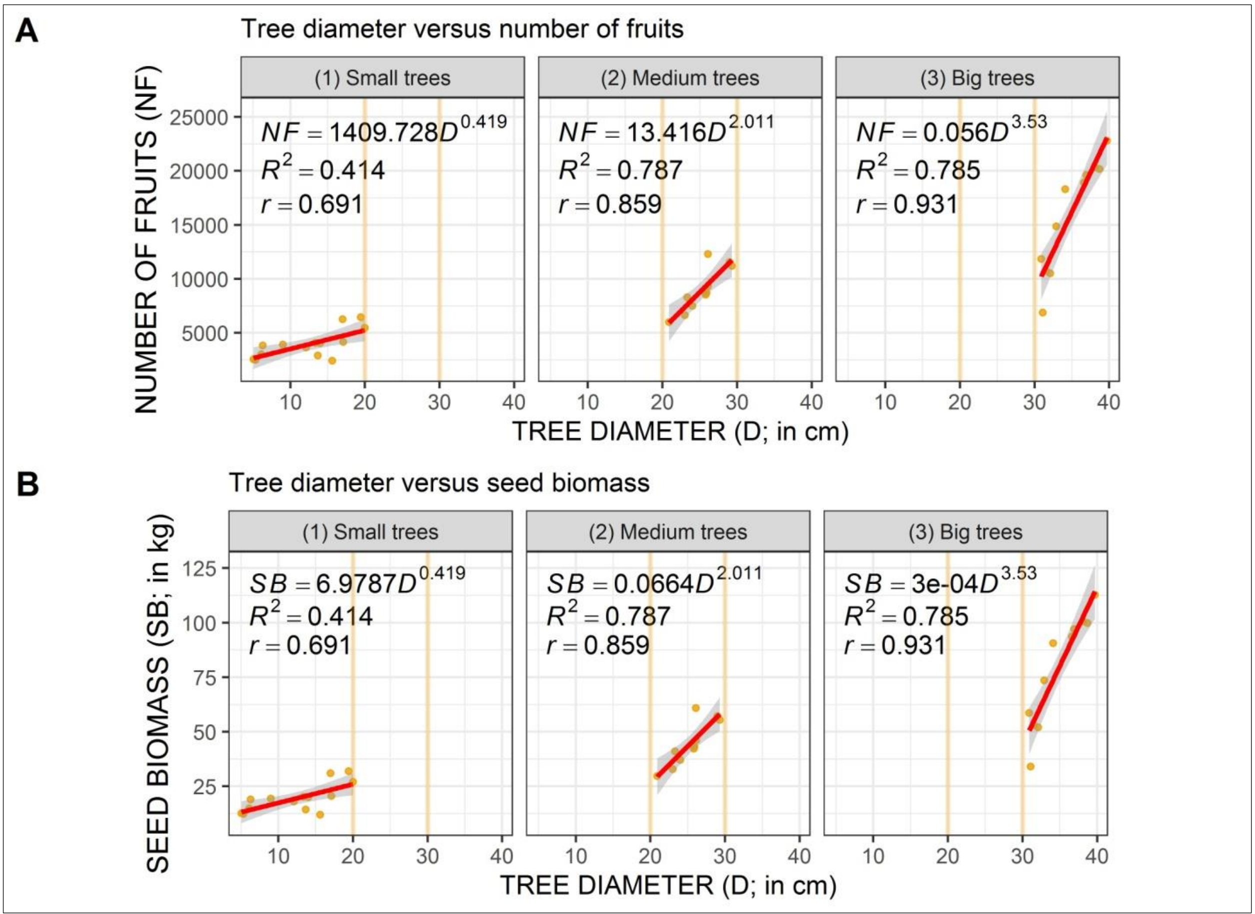
$SB = 0.0003 \times DBH^{3.53}$ (Chap7-Equation 11) for the number of fruits on the trees (NF) and the seed biomass (SB; in kg). Prediction curves of these tree size category models showed minimized standard error trends for both the number of fruits (Chap7-Figure 8A) and the seed biomass of *T. emetica* (Chap7-Figure 8B).

Chap7-Table 3: Fitting of the coefficients of the models that link the number of fruits and the seed biomass (in kg) to the tree parameters. The estimation of the coefficients "a_0, a_1, a_2" is done at the confidence interval of 95% (and their margins are in brackets). The coefficient of determination (R^2) and the Akaike information criteria (AIC) are given for each model. The best models, according to the considered fitting criteria, are hatched in grey.

Model	Coefficients of the models			R^2	AIC
	a_0	**a_1**	**a_2**		
Fruit count					
Model 1	5.876 [5.592 – 6.161]	1.009 [0.916 – 1.102]	-	0.78	23.58
Model 2	-0.108 [-1.53 – 1.314]	1.384 [1.166 – 1.602]	-	0.54	48.83
Model 3	5.520 [4.660 – 6.381]	1.997 [1.493 – 2.501]		0.30	63.14
Model 4	5.534 [5.044 – 6.025]	0.952 [0.838 – 1.067]	0.301 [-0.05 – 0.654]	0.77	24.78
Model 5	1.971 [0.516 – 3.426]	1.203 [0.916 – 1.491]	0.521 [-0.019 –1.063]	0.53	49.82
Model 6	4.969 [3.651 – 6.288]	0.921 [0.765 – 1.077]	0.179 [-0.07 – 0.434]	0.77	25.04
Seed biomass					
Model 1	0.568 [0.283 – 0.852]	1.009 [0.916 – 1.102]	-	0.77	23.57
Model 2	-5.416 [-6.838– -3.994]	1.384 [1.166 – 1.602]	-	0.53	48.83
Model 3	0.212 [-0.647– 1.072]	1.997 [1.493 – 2.501]	-	0.30	63.14
Model 4	0.226 [-0.264– 0.717]	0.952 [0.838 – 1.067]	0.301 [-0.05 – 0.654]	0.77	24.78
Model 5	-5.128 [-6.58– -3.673]	1.203 [0.916 – 1.491]	0.522 [-0.019 – 1.06]	0.53	49.82
Model 6	-0.338 [-1.65 – 0.979]	0.921 [0.765 – 1.077]	0.179 [-0.075– 0.434]	0.77	25.04



Chap7-Figure 7: Prediction curves of the number of fruits (A), and the seed biomass (B) of *Trichilia emetica*. The fitted linear equation (also presented in red curve), the standard error (the grey zone surrounding the red curve), the coefficient of determination (R^2), and the correlation factor (*r*) are given for each relationship. Vertical orange lines show standard error shift zones.



Chap7-Figure 8: Prediction curves of the number of fruits (A) and the seed biomass (B) of *Trichilia emetica* by categories of the diameter at breast height (DBH) and tree size. Vertical orange lines delimit DBH categories. The fitted equations (also presented in red curves), the standard error (the grey zone surrounding the red curves), the coefficient of determination (R^2), and the correlation factor (r) are given for each category.

7.5.4. Prediction tests of the fitted models

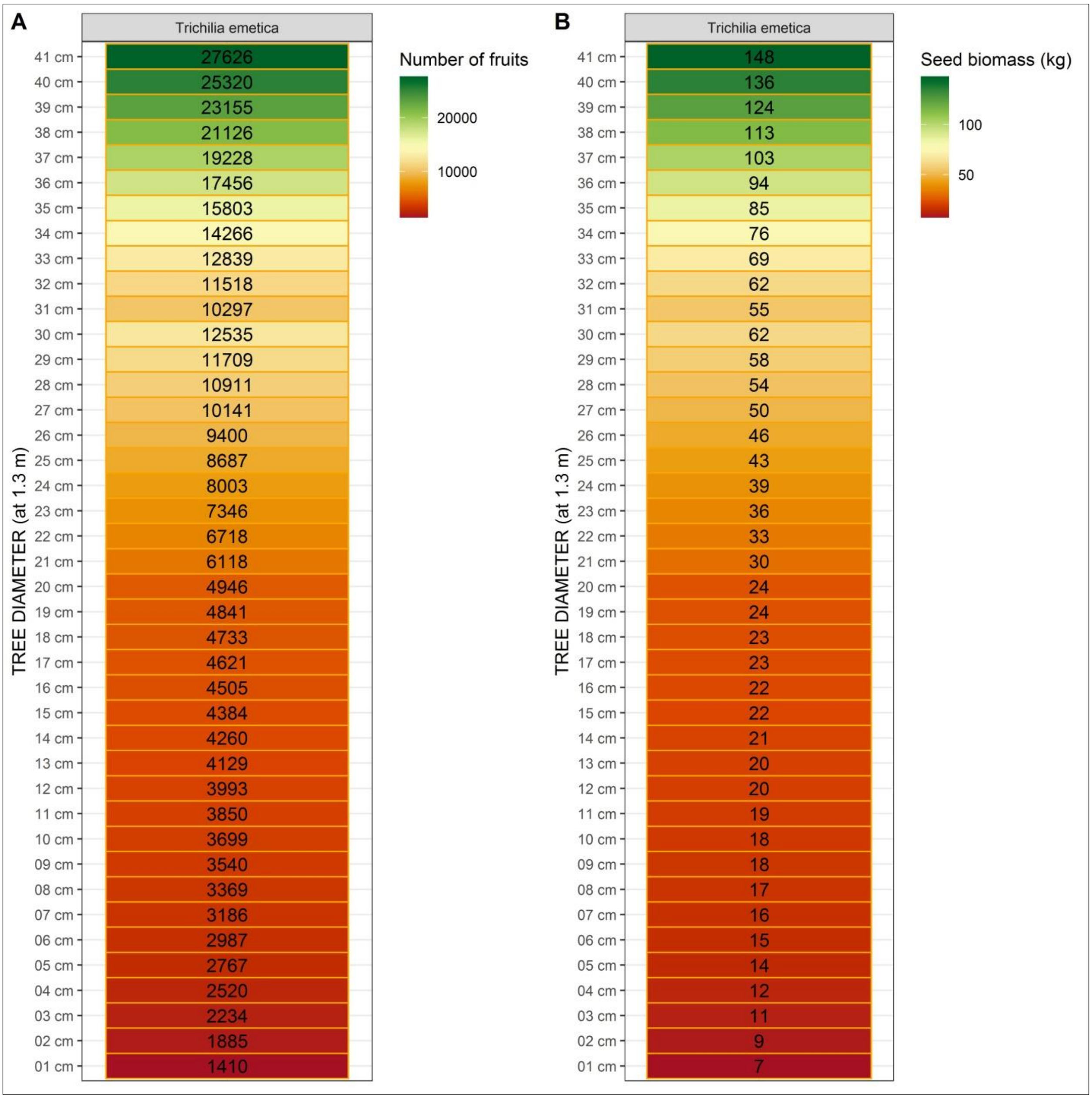
The Student test used to compare the measured and the predicted number of fruits and seed biomass of *T. emetica* indicated significant differences when using general models for small trees and big trees (*p-value* < 0.05; Chap7-Table 4). General models gave realistic predictions only for trees that covered DBH class 5 and 6 (*p-value* > 0.05; Chap7-Table 4). The tree size category models were not liable to prediction errors (Chap7-Table 5). However, for these models, prediction error was only observed with the seed biomass in DBH class 7 (Chap7-Table 5). Based on these improved models, a practical conversion scale was developed for both the number of fruits (Chap7-Figure 9A) and the seed biomass of *T. emetica* (Chap7-Figure 9B).

Chap7-Table 4: Prediction tests of fruit count and seed biomass models by diameter at breast height (DBH) category. The *p-value* of the Student test is reported at 95% confidence interval. Mean values of number of fruits (NF) and seed biomass (SB) are predicted using bolded equations. Biased predictions (where *p-value* < 0.05) are hatched in grey.

DBH category (cm)	Mean number of fruits of trees			Mean seed biomass (kg)		
	measured	predicted	*p-value*	measured	predicted	*p-value*
	NF = 375.364 × *DBH* $^{\mathbf{1.009}}$			**SB = 1.858 × *DBH*** $^{\mathbf{1.009}}$		
Class 1 [5, 10.9]	3164	2426	0.014	15.6	12.0	0.015
Class 2 [11, 15.9]	3418	5287	0.018	16.9	26.1	0.018
Class 3 [16, 20.9]	5660	7279	0.017	28.0	36.0	0.017
Class 4 [21, 25.9]	7929	9426	0.004	39.2	46.7	0.004
Class 5 [26, 30.9]	11240	10939	0.587	55.6	54.1	0.587
Class 6 [31, 35.9]	12251	12527	0.883	60.6	62.0	0.883
Class 7 [36, 40.9]	20350	14743	0.0002	100.7	72.9	0.0002

Chap7-Table 5: Prediction tests of fruit count and seed biomass models by diameter at breast height (DBH) and tree size category. The *p-value* of the Student test is reported at 95% confidence interval. Mean values of number of fruits (NF) and seed biomass (SB) are predicted using bolded equations. Biased predictions (where *p-value* < 0.05) are hatched in grey.

DBH category (cm)	Mean number of fruits of trees			Mean seed biomass (kg)		
	measured	predicted	*p-value*	measured	predicted	*p-value*
Small trees	**NF = 1409.728 × *DBH*** $^{\mathbf{0.419}}$			**SB = 6.978 × *DBH*** $^{\mathbf{0.419}}$		
Class 1 [5, 10.9]	3164	3043	0.593	15.6	15.1	0.593
Class 2 [11, 15.9]	3418	4225	0.096	16.9	20.9	0.096
Class 3 [16, 20.9]	5660	4824	0.099	28.0	23.8	0.099
Medium trees	**NF = 13.416 × *DBH*** $^{\mathbf{2.011}}$			**SB = 0.066 × *DBH*** $^{\mathbf{2.011}}$		
Class 4 [21, 25.9]	7929	8294	0.261	39.2	40.8	0.322
Class 5 [26, 30.9]	11240	11181	0.940	55.6	55.0	0.870
Big trees	**NF = 0.056 × *DBH*** $^{\mathbf{3.53}}$			**SB = 0.0003 × *DBH*** $^{\mathbf{3.53}}$		
Class 6 [31, 35.9]	12251	12021	0.867	60.6	64.4	0.572
Class 7 [36, 40.9]	20350	21234	0.199	100.7	113.7	0.016



Chap7-Figure 9: Practical conversion scale of the number of fruits (A) and seed fresh biomass (B) of *Trichilia emetica* by tree diameter unit.

7.6. Discussion

Commercial harvesting of fruits and seeds from the wild presents a business opportunity for the local communities in rural areas. Nevertheless, to venture in this business, one needs to compare the cost of investment and the possible income. This can be done based on the prices of products and services in the local markets. Thereafter, one can know the amount of fruits/seeds that will be necessary to make profit. However, one cannot be sure about the amount of fruits/seeds to expect from trees or a forest stand. Consequently, venturing into commercial harvest of indigenous fruit tree species incurred a risk. Fortunately, this study provided allometric equations that will enable the prediction of fruit and seed yields of *T. emetica*. These equations linked the tree parameters to the number of fruits and the biomass of seeds. It was demonstrated that the diameter at breast height (DBH) of the trees was the best predictor of both the number of fruits on a tree and its seed biomass. Likewise other studies on fruit allometry (Akweni et al. 2020), simple linear regression basing on DBH was the best model formulation. Other tree parameters such as the height and the crown diameter were not appropriate to predict the number of fruits and the seed biomass of the trees. This implies that one will only need to measure the DBH of a tree (regardless of other tree parameters) and use the fitted equations to predict its number of fruits and seed biomass. Concerning the equations to use, this study revealed that general equations, fitted at the species level, were liable to significant prediction errors. The equations that were developed following the tree size categories were more accurate as they minimized both the standard deviations (Chap7-Figure 8) and the prediction errors (Chap7-Table 5). Therefore, Chap7-Equation 6, 7, 8, 9, 10, and 11 are the ones suggested for use. The prediction errors can be explained by the methods used to count fruit and to derive the seed biomass. The fruits were counted using randomized branch sampling technique developed by Jessen (1955) and later improved by Pearce and Holland (1957). Since, the technique of fruit count has not substantially evolved except for those species whose fruits can easily be counted. The branch sampling technique considers a mean value from selected fruiting branches as a reflection of all other fruiting branches. In reality, there can be large variations in terms of number of fruits between branches of the same fork (Chap7-Figure 2). However, this technique saves time and remains statistically tolerable than attempting to count all the fruits on the trees. Chap7-Figure 4D revealed that *T. emetica* can bear up to 22770 fruits. Branch sampling was therefore necessary to save time.

The prediction equations developed in this study can serve as decision tools for harvesters. However, in rural areas most of harvesters do not have enough knowledge to understand and use mathematical expressions in the field. For practical purposes, this study created a printable conversion scale that harvesters can use in the field to predict the number of fruits and the seed biomass of trees as they measure their diameters (Chap7-Figure 9). This conversion scale is very important in the preparation of a commercial harvest based on the fruits and seeds of *T. emetica*. From the scale, the number of seeds can be determined by multiplying the number of fruits by six. Chap7-Table 2 indicated that there were constantly six seeds inside each fruit. In addition, the amount of oil can be derived from the seed biomass using reported oil yield ratios. For example, Grundy and Campbell (1993) mentioned that 1 kg of fresh seeds yields about 308 ml of oil, approximately 30%. This rate can therefore be applied to any amount of fresh seed biomass to generate an estimate of oil. Yet, one should be careful because many oil rates of *T. emetica* are reported in the literature. Recently, Nchimbi (2020) reported that the oil yield of *T. emetica* represents 48.4−50.2% of the seed biomass. This rate is relatively higher than that of Grundy and Campbell (1993). However, Amália and Samuel (2016) pointed out that slight variations in the oil rates of *T. emetica* are possible when considering the provenance of seeds. Moreover, methods of oil extraction can also be a source of differences. Several traditional extraction techniques of the seed oil of *T. emetica* are not formally reported. Further studies are necessary to set reliable ranges of oil yield of *T. emetica.*

It is important to note that the allometric equations developed in this study were obtained from the data emanating from the trees that were located along the road sides. None of the trees naturally growing in the forest was investigated. Thus, using the equations developed in this study for the trees that grow in different ecological zones may also be source of prediction errors, especially for the fruit yield. The influence of landscape factors (such as the proximity of road) on the productivity of *T. emetica* needs to be investigated. The fruit yield of *T. emetica* is subject to seasonal variations, sometimes from one year to the next (Grundy and Campbell 1993). The seed yield per tree can vary from 20 to 180 kg/year (Mashungwa and Mmolotsi 2007). The current study did not consider the seasonal variation of biomass production as the data were collected during one fruiting season. The extension of such study over several years can contribute towards minimizing the seasonal effect in the fruit/seed biomass production.

7.7. Conclusion

This study developed allometric equations that enable the prediction of the amount of fruits and seeds (including oil) that can be produced by the trees of *Trichilia emetica.* These equations are important in the advent of commercially harvesting the fruits and the seeds from the wild. They will contribute in the stage of making cost-benefit analysis of a harvest project by providing an estimate of the expected production of trees. This estimate will also play a crucial role in the understanding of physiological and environmental factors that influence the productivity of the trees of *T. emetica*.

CHAPTER 8: GENERAL DISCUSSION

Application of allometric equations in the valorization of fruit tree species

The province of KwaZulu-Natal has large expanses of natural vegetation that contain numerous indigenous fruit tree species. In rural areas, fruit tree species play a crucial role in the well-being of local communities. They are used as an alternative source of food and medicine. The trees also provide multiple services and products such as fire wood, alkaloids, oils, shade, among others. The fruit biomass estimations carried out in Chapter 6, at municipality level, proved that savannah woodlands in the northern coastal plain of KwaZulu-Natal have the potential to produce high amounts of *Strychnos* fruits that can sustain large-scale ventures based on harvesting the fruits from the wild. The *Strychnos* fruits and other indigenous edible fruits in the province are restricted to domestic consumption, and no case of agribusiness development has been reported so far. Among the reasons that hinder the development of large-scale commercial ventures of indigenous fruits is the difficulty to estimate and predict their wild biomass. This study pioneered fruit-based allometry of three important fruit tree species in KwaZulu-Natal, namely: *S. madagascariensis*, *S. spinosa*, and *T. emetica*. In this regards, allometric equations that linked dimensions of the trees to the fruit biomass were developed (Chapters 4 and 7), making it possible to estimate and predict the fruit biomass from the wild. For all the three species studied, the diameter at breast height (DBH) was the most important tree parameter in the prediction of the fruit biomass (Chapters 4 and 7). In addition, the fruit diameter was also an important parameter in the derivation of biomass allocation and carbon stocks in fruit components of *S. madagascariensis* and *S. spinosa* species (Chapter 5). It was also revealed that fixed values of proportions were a valid alternative technique to derive biomass allocation in fruit components of *S. madagascariensis* and *S. spinosa* (Chapter 5).

The fruit-based allometric equations developed in this study have several scientific and commercial applications. Scientifically, these equations are useful in providing a non-destructive estimation of biomass and C stocks channeled to fruits. This presents an important ecological benefit as it prevents the destruction of biodiversity. In addition, the regression models developed for fruit components also enable a non-destructive derivation of fresh and dry biomass of fruit shell, pulp, seeds, juice, and oil. For *S. spinosa*, the derivation of puree and juice from the fruit diameter (Chapter 5) is very strategic in the immediate evaluation of their yield without having to resort to time-consuming processes of extracting them. Commercially, these fruit-based and fruit-components-based equations represent an important achievement towards the valorization and commercial exploitation of indigenous fruit tree species. The developed equations in Chapters 4, 5, and 7 make it possible to evaluate the commercial value of savanna ecosystems. Furthermore, this evaluation can be extended to the fruit by-products. The equations developed in this study can also serve as decision tools for harvesters and manufacturers of the products from the fruits. For example, the equations can allow them to know, early in the season, the harvestable amount of fruits in the wild. In addition to providing estimates of the amount of useful/economic products, they also provide the amounts of wastes that would need to be taken off in one way or another. This will enable them to relate their efforts of harvest to the expected income and waste management.

The printable conversion scale developed in this study for *T. emetica* also has a practical and valuable commercial importance. It can allow harvesters to predict the number of fruits and the seed biomass of trees from diameter measurements. This will facilitate the decision making process in the preparation for commercial harvests of *T. emetica* seeds for oil extraction. From the scale, the amount of oil can also be derived from the seed biomass using reported oil yields. This is an outstanding achievement towards the commercialization of the oil of *T. emetica*. This can encourage entrepreneurship in rural areas and facilitate economic feasibility studies of commercial harvest ventures.

It should however be noted that all the allometric models and tools developed in this study can only be used for the species studied. Similar studies need to be undertaken for other indigenous fruit tree species of the province.

In general the developed allometric equations for fruit biomass estimations and predictions of *Strychnos* and *Trichilia* species have the potential to initiate commercial utilization of these species in all areas in which the species occur in Africa. Perhaps, this will encourage governmental entities to invest in an industrial processing and harvesting of the fruits to tackle poverty in rural areas and promote local employments.

There are some limitations in the use of the allometric equations derived in the present study. The issue of seasonality, which was not addressed in this study, might negatively impact on fruit supply in some years. The productivity of *S. madagascariensis*, *S. spinosa*, and *T. emetica* are subject to variations following the seasons. Seasonal variation in fruit productivity can be substantial. It is therefore worthwhile to invest effort researching on this aspect in future studies.

In the case of low productivity say due to drought, the equations developed in this study will overestimate the fruit biomass of trees. This overestimation can be much larger if the equations are used in larger areas. In addition, there are other factors that can cause the overestimation of the fruit biomass. These include (1) the need to leave some fruits to sustain adequate natural regeneration; (2) the loss of fruits due to frugivore species; (3) the damage to some fruits from pests and diseases; (4) and the loss of fruits on the ground due to wildfires. These factors were not accounted for in the development of the equations presented in this study. One of the solutions to the above problems is the development of correction factors which will consider the above-mentioned sources of biomass overestimation to provide realistic predictions. Further studies are necessary to address such corrections.

CHAPTER 9: GENERAL CONCLUSION

This study (1) developed allometric equations for estimating fresh fruit biomass of *S. madagascariensis* and *S. spinosa*; (2) established techniques to derive biomass allocation and carbon stocks of fruit components of *S. madagascariensis* and *S. spinosa*; (3) investigated fruit biomass production potential of savannah woodlands; and (4) calibrated allometric equations that enable the prediction of the amount of fruits and seeds (including oil) of *Trichilia emetica* from the wild. The results of the present study revealed a high commercialization potential of *S. madagascariensis, S. spinosa*, and *T. emetica* in KwaZulu-Natal. It was ascertained that the fruit biomass production per surface unit of savannah woodlands was high enough to ensure profitable harvest of the fruits from the wild. This can create business opportunities for local harvesters. Allometric equations developed in this study can also be used by scientific communities to evaluate the ecological contribution of fruit tree species in regulating carbon balance of savannah woodlands. However, the fruit-based allometric equations developed in this study need to be validated using neutral data. In addition, sources of under and overestimation of fruit biomass need to be considered when using the equations.

LIST OF REFERENCES

Adinew B. 2014a. Biodiesel production from Trichilia emetica seeds using in-situ transesterification. *Bulgarian Chemical Communications* 46(2): 334-338.

Adinew B. 2014b. Physico-chemical properties of Trichilia emetica seeds oil and its comparison with some selected oilseed oils. *Bulgarian Chemical Communications* 46(2): 330-333.

Adinew B. 2015. Minerals and fatty acid composition analysis of Trichilia emetica seed oil and the possibility of its use in cosmetic preparation. *World Journal of Pharmacy and Pharmaceutical Sciences* 3: 2321-3086.

Akaike H. 1974. A new look at the statistical identification model. *IEEE Transactions on Automatic Control* vol. 19, pp 716-723.

Akweni AL, Sibanda S, Zharare GE, Zimudzi C. 2020. Fruit-based allometry of Strychnos madagascariensis and S. spinosa (Loganiaceae) in the savannah woodlands of the Umhlabuyalingana municipality, KwaZulu-Natal, South Africa. *Trees*, *Forests and People* 2 (2020) 100025.

Akweni AL, Sibanda S, Zharare GE, Zimudzi C. 2021. Datasets supporting fruit components biomass and carbon stocks derivation of Strychnos madagascariensis and S. spinosa. Mendeley Data, V1. Doi: 10.17632/xczzcyjd69.1. https://data.mendeley.com/datasets/xczzcyjd69/1.

Alemdag I. 1981. Equations de masse pour la portion epigée de six essences de feuillus dans des peuplements naturels de la forêt experimentale de Petawawa. *Canadian Forestry Service*.

Amália U, Samuel OY. 2016. A comparative study of the oils from the seed arils of Trichilia emetica from Mozambique. *International Journal of Agricultural Sciences*: 2016:1172.

Amara E, Adhikari H, Heiskanen J, Siljander M, Munyao M, Omondi P, Pellikka P. 2020. Aboveground Biomass Distribution in a Multi-Use Savannah Landscape in Southeastern Kenya: Impact of Land Use and Fences. *Land* 9 (10): 381.

Archibald S, Bond W. 2003. Growing tall vs growing wide: tree architecture and allometry of *Acacia karroo* in forest, savanna, and arid environments. *Oikos* 102 (1): 3–14.

Arráez-Aybar LA, Bueno-López JL, Moxham BJ. 2014. Anatomists' views on human body dissection and donation: An international survey. *Annals of Anatomy-Anatomischer Anzeiger* 196 (6): 376-386.

Arunkumar P, Sadish Kumar V, Saran S, Bindun H, Devipriya SP. 2019. Isolation of active coagulant protein from the seeds of Strychnos potatorum - a potential water treatment agent. *Environmental technology* 40(12): 1624-1632.

Avakoudjo HGG, Hounkpèvi A, Idohou R, Koné MW, Assogbadjo AE. 2020. Local Knowledge, Uses, and Factors Determining the Use of Strychnos spinosa Organs in Benin (West Africa). *Economic Botany* 74(1): 15-31.

Banda T, Schwartz MW, Caro T. 2006. Woody vegetation structure and composition along a protection gradient in a miombo ecosystem of western Tanzania. *Forest ecology and management* 230 (1-3): 179-185.

Basu P. 2018. Introduction. In: *Biomass Gasification, Pyrolysis and Torrefaction*. Academic Press. Practical design and Theory (3rd edn). pp1-27.

Bauwens S, Fayolle A. 2014. Protocole de collecte des données sur le terrain et au laboratoire nécessaires pour quantifier la biomasse aérienne des arbres et pour l'établissement d'équations allométriques. ULiège- Gembloux Agro-Bio Tech. Nature+. http://hdl.handle.net/2268/170397.

Beaufay C, Ledoux A, Jansen O, Bordignon A, Zhao S, Teijaro CN, Andrade RB, Quetin-Leclercq J, Frédérich M. 2018. In vivo Antimalarial and Antitrypanosomal Activity of Strychnogucine B, a Bisindole Alkaloid from Strychnos icaja. *Planta medica* 84 (12-13): 881-885.

Bettencourt LM, Lobo J, Helbing D, Kuhnert C, Geoffrey BW. 2007. Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences* 104 (17): 7301.

Biyela AC, Nzimakwe TI, Mthuli SA, Khambule I. 2018. Assessing the Role of Intergovernmental Relations in Strategic Planning For Economic Development at Local Government Level: A Case Study of Umkhanyakude District Municipality. *Journal of Gender, Information & Development in Africa* 7 (2): 221-239.

Bohlman S, O'Brien S. 2006. Allometry, adult stature and regeneration requirement of 65 tree species on Barro Colorado Island, Panama. *Journal of Tropical Ecology* 22 (2).

Boon R. 2010. Pooley's trees of Eastern South Africa, a complete guide. *Flora & Fauna Publications Trust*, Totnes.

Botha G, Porat N. 2007. Soil chronosequence development in dunes on the southeast African plain, Maputaland, South Africa. *Quaternary International* 162: 111-132.

Brown S, Lugo A. 1982. The storage and production of organic matter in tropical forests and their role in the global carbon cycle. *Biotropica* 14: 161-187.

Brown S, Gillespie A, Lugo A. 1989. Biomass Estimation Methods for Tropical Forests with Application to Forest Inventory Data. *Forest Science* 35 (4): 881-902.

Brown S, Lugo A. 1992. Above ground biomass estimates for tropical moist forests of the Brazilian Amazon. *Interściencia* 17: 8-18.

Burgess N, Hales JA, Underwood E, Dinerstein E, Olson D, Itoua I, Schipper J, Ricketts T, Newman K. 2004. Terrestrial ecoregions of Africa and Madagascar: a conservation assessment. *Island Press*: 2004.

Bussmann RW, Paniagua-Zambrana NY, Njoroge GN. 2021. *Trichilia emetica* Vahl Meliaceae. *Springer International Publishing* 2021. Ethnobotany of the Mountain Regions of Africa. pp 1041-1044. Doi:10.1007/978-3-030-38386-2_161.

Byers JP, Sarver JG. 2009. Pharmacokinetic modeling. *In Pharmacology Academic Press* pp. 201-277.

Campbell B, Frost P, Byron N. 1996. Miombo woodlands and their use: overview and key issues. In: Campbell B (ed.), *The miombo in transition: woodlands and welfare in Africa*. Bogor: Center for International Forestry Research. pp 1–5.

Carreiras J, Melo J, Vasconcelos M. 2013. Estimating the Above-Ground Biomass in Miombo Savanna Woodlands (Mozambique, East Africa) Using L-Band Synthetic Aperture Radar Data. *Remote Sensing Journal* 5: 1524-1548.

Chambers J, Santos JD, Ribeiro R, Higuchi N. 2001. Tree damage, allometric relationship, and above-ground net primary production in central Amazon forest. *Forest Ecology and Management* 73-84.

Chapman CA, Chapman LJ, Wangham R, Hunt K, Gebo D, Gardner L. 1992. Estimators of fruit abundance of tropical trees. *Biotropica* 527-531.

Chavan BL, Rasal GB. 2011. Potentiality of Carbon Sequestration in six year ages young plant from University campus of Aurangabad. Global Journal of Researches in Engineering (7):15-20.

Chave J, Riéra B, Dubois MA. 2001. Estimation of biomass in a neotropical forest of French Guiana: spatial and temporal variability. *Journal of Tropical Ecology* 17(1): 79–96.

Chave J, Condit R, Aguilar S, Hernandez A, Lao S, Perez R. 2004. Error propagation and scaling for tropical forest biomass estimates. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* 359 (1443): 409-420.

Chave J, Andalo C, Brown S, Cairns M, Chambers J, Eamus D, Fölster H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson BW, Ogawa H, Puig H, Riéra B, Yamakura T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* (1) 145: 87-99.

Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan M, Delitti W, Duque A, Eid T, Fearnside P, Goodman R, Henry M, Martínez-Yrízar A, Mugasha W, Muller H, Mencuccini M, Nelson B, Ngomanda A, Nogueira E, Ortiz E, Pélissier R, Ploton P, Ryan C, Saldarriaga J, Vieilledent G. 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. *Global change biology* 20 (10): 3177-3190.

Chen X, Hutley LB, Eamus D. 2003. Carbon balance of a tropical savanna of northern Australia. *Oecologia* 137(3): 405-416.

Chidumayo, E. 2013. Forest degradation and recovery in a miombo woodland landscape in Zambia: 22 years of observations on permanent sample plots. *Forest Ecology and Management* 291: 154-161.

Daba DE, Soromessa T. 2019. The accuracy of species-specific allometric equations for estimating above ground biomass in tropical moist montane forests: case study of Albizia grandibracteata and Trichilia dregeana. *Carbon Balance & Management* 14(1): 1-13. Doi:10.1186/s13021-019-0134-8.

de Miranda SDC, Bustamante M, Palace M, Hagen S, Keller M, Ferreira LG. 2014. Regional variations in biomass distribution in Brazilian savanna woodland. *Biotropica* 46 (2): 125-138.

Delaude C, Thepenier P, Jacquier MJ, Massiot G, Le Men-Olivier L. 1992. Contribution to the study of African Strychnos: alkaloïds of Strychnos cocculoides, Strychnos lucens, Strychnos madagascariensis, Strychnos minfiensis, Strychnos mitis, Strychnos pungens and Strychnos spinosa. *Bulletin de la Société Royale des Sciences de Liège* 61(6): 429-440. Accessed October 17, 2020.

Diallo D, Paulsen BS, Liljebäck THA, Michaelsen TE. 2003. The malian medicinal plant Trichilia emetica; studies on polysaccharides with complement fixing ability. *Journal of ethnopharmacology* 84(2-3): 279-287.

Dietze M, Wolosin M, Clark J. 2008. Capturing diversity and interspecific variability in allometries: A hierarchical approach. *Forest Ecology and Management* 256 (11): 1939–1948.

Dimobe K, Mensah S, Goetze D, Ouédraogo A, Kuyah S, Porembski S, Thiombiano A. 2018. Aboveground biomass partitioning and additive models for Combretum glutinosum and Terminalia laxiflora in West Africa. *Biomass and Bioenergy*, 115, 151-159.

Djomo A, Ibrahima A, Saborowski J, Gravenhorsta G. 2010. Allometric equations for biomass estimations in Cameroon and pan moist tropical equations including biomass data from Africa. *Forest Ecology and Management* 260 (10): 1873-1885.

Drimie S, Ngcobo N, Mambo J. 2008. Oxfam Australia evaluation report: Umkhanyakude partnership programme. (2008) 70 pp. Link: Oxfam Australia evaluation report: Umkhanyakude partnership programme. Accessed August 9th, 2021.

Duan N. 1983. Smearing estimate: a nonparametric retransformation method. *Journal of the American Statistical Association* 78, 605-610.

Ebuy J, Lokombe J, Ponette Q, Sonwa D, Picard N. 2011. Allometric equation for predicting aboveground biomass of three tree species. *Journal of Tropical Forest Science* vol. 23:125-132.

Edomah N. 2018. Economics of Energy Supply. In: Edomah N (eds), *Reference Module in Earth Systems and Environmental Sciences*. 2018.

Elago SN, Tjaveondja LT. 2015. Socio-economic importance of two indigenous fruit trees: Strychnos cocculoides and Schinziophyton rautanenii to the people of Rundu Rural West Constituency in Namibia. *European Journal of Physical and Agricultural Sciences* Vol 3(2).

Encyclopedia of Public Health. 2008. Kirch Wilhelm, 2008. Springer Netherlands. ISBN 978-1-4020-5614-7.

FAO (Food and Agriculture Organization). 2006. Global Forest Resources Assessment 2005. Progress towards sustainable forest management. *FAO Forestry Paper* vol. 147, Rome.

Fayolle A, Doucet JL, Gillet JF, Bourland N, Lejeune P. 2013a. Tree allometry in Central Africa: Testing the validity of pantropical multi-species allometric equations for estimating biomass and carbon stocks. *Forest Ecology and Management* 305: 29-37.

Fayolle A, Rondeux J, Doucet JL, Ernst G, Bouissou C, Quevauvillers S, Bourland N, Fétéke R, Lejeune P. 2013b. Réviser les tarifs de cubage pour mieux gérer les forêts du Cameroun. *Bois et Forêts des Tropiques* 317 (3): 35-49.

Fekadu M, Yohannes T. 2004. Economic value of Trichilia emetica, Delonix elata, Berchemia discolor and Warburgia ugandensis in Ethiopia. *Ethiopian Agricultural Research Organization* 2004: 88-93. Conference paper. Accessed May 14, 2021.

Focardi S. 2008. Biomass, Gross Production, and Net Production. Encyclopedia of Ecology. 2008, pp 453-461.

Fortier J, Truax B, Gagnon D, Lambert F. 2017. Allometric equations for estimating compartment biomass and stem volume in mature hybrid Poplars: General or Site-specific? *Forests* 8 (9): 309.

Frost PG, Medina E, Menaut J, Solbrig O, Swift M, Walker B (eds). 1986. *Responses of savannas to stress and disturbance*. The News Magazine of the International Union of Biological Sciences.

Gajewski J, Buśko K, Mazur J, Michalski R. 2011. APPLICATION OF ALLOMETRY FOR DETERMINATION OF STRENGTH PROFILE IN YOUNG FEMALE ATHLETES FROM DIFFERENT SPORTS. *Biology of Sport* 28 (4).

Gautam S, Arora AS, Singh AK, Ekka P, Daniel H, Gokul B, Toppo S, Chockalingam P, Kumar H, Lyngdoh JF. 2021. Coagulation influencing parameters investigation on textile industry discharge using Strychnos potatorum seed powders. *Environment, Development and Sustainability* 23 (4), 5666-5673.

Gayon J. 2000. History of the Concept of Allometry. *American Zoologist* 40 (5): 748-758.

Germano MP, D'angelo V, Sanogo R, Catania S, Alma R, De Pasquale R, Bisignano G. 2005. Hepatoprotective and antibacterial effects of extracts from Trichilia emetica Vahl. (Meliaceae). *Journal of ethnopharmacology* 96(1-2): 227-232.

Gibbs HK, Brown S, Niles JO, Foley JA. 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environmental research letters* 2 (4): 045023.

Giovas CM, Fitzpatrick SM, Kataoka O, Clark M. 2016. Prey body size and anthropogenic resource depression: The decline of prehistoric fishing at Chelechol ra Orrak, Palau. *Journal of Anthropological Archaeology* 41: 132-146.

Gould SJ. 1966. Allometry and size in ontogeny and phylogeny. *Biological reviews* 41: 587-640.

Govender L, Pillay K, Siwela M, Modi A, Mabhaudhi T. 2017. Food and Nutrition Insecurity in Selected Rural Communities of KwaZulu-Natal, South Africa-Linking Human Nutrition and Agriculture. *International Journal of Environmental Research and Public Health* 14 (1): 17.

Grouard S, Perdikaris S, Espindola-Rodrigues NE, Quitmyer IR. 2019. Size estimation of pre-Columbian Caribbean fish. *International Journal of Osteoarchaeology* 29 (3): 452-468.

Grundy IM, Campbell BM. 1993. Potential production and utilization of oil from Trichilia spp. (Meliaceae). *Economic Botany* 47: 148–153.

Hales JR, Stanton L, Reitz EJ. 1992. Historical changes in age and growth of Atlantic croaker, Micropogonias undulatus (Perciformes: Sciaenidae). *Journal of Archaeological Science* 19 (1): 73-99.

Harmse A. 2010. Node selection for the Integrated Sustainable Rural Development Programme in South Africa. *Development Southern Africa* 27 (3): 429-445.

Hassan H, Omoniyi KI, Okibe FG, Nuhu AA, Echioba EG, Egwim EC. 2020. Assessment of Wound Healing Activity of Green Synthesized Titanium Oxide Nanoparticles using Strychnos spinosa and Blighia sapida. *Journal of Applied Sciences & Environmental Management* 24(2):197-206.

He W, Wang P, Chen J, Xie W. 2020. Recent progress in the total synthesis of Strychnos alkaloids. *Organic & biomolecular chemistry* 18(6):1046-1056.

Henry M, Besnardd A, Asantee W, Eshunf J, Adu-Bredug S, Valentinic R, Bernouxb M, Saint-Andréh L. 2010. Wood density, phytomass variations within and among trees, and allometric equations in a tropical rainforest of Africa. *Forest Ecology and Management* 260(8): 1375-1388.

Holdo RM. 2006. Tree Growth in an African Woodland Savanna Affected by Disturbance. *Journal of Vegetation Science* 17 (3): 369-378.

Houghton RA. 2008. Biomass. In: Jorgensen SE, Fath BD (eds), *Encyclopedia of Ecology* (1st ed.), Elsevier (2008), pp 448-453.

IDP (Integrated Development Plan). 2017. Umhlabuyalingana Municipality Integrated Development Plan 2015-2016. Available at www.umhlabuyalingana.gov.za/docs/idp/20170606/FINAL_2015-2016.pdf [accessed 20 February 2020].

IDP (Integrated Development Plan). 2018. Umhlabuyalingana Municipality Integrated Development Plan 2018-2019. Available at www.umhlabuyalingana.gov.za/wp-content/uploads/2018/10/UMHLABUYALINGANA_LOCAL_MUNICIPALITY_2018_2019_FINAL_IDP.pdf [accessed 10 August 2021].

Isa AI, Awouafack MD, Dzoyem JP, Aliyu M, Magaji RA, Ayo JO, Eloff JN. 2014. Some Strychnos spinosa (Loganiaceae) leaf extracts and fractions have good antimicrobial activities and low cytotoxicities. *BMC complementary and alternative medicine* 14: 456.

Jackson K, Southard E, O'Donnell S, Arthur J. 2018. Estimating crown conch (Melongena corona) tissue weight from archaeological shell measurements: An allometric methodology for coastal historical ecological research. *Journal of Archaeological Science* Report 21: 107-116.

Jana BK, Biswas S, Majumder M, Roy PK, Mazumdar A. 2009. Carbon sequestration rate and aboveground biomass carbon potential of four young species. *Journal of Ecology and Natural Environment* 1(2): 15-24.

Jessen RJ. 1955. Determining the fruit count on a tree by randomized branch sampling. *Biometrics* 11: 99-109.

Jewitt D. 2018. Vegetation type conservation targets, status and level of protection in KwaZulu-Natal in 2016. *Bothalia - African Biodiversity & Conservation*. ISSN: 2311-9284.

Jiménez-Cano, Nayeli G, Masson MA. 2016. Estimation of fish size from archaeological bones of hardhead catfishes (Ariopsis felis): Assessing pre-Hispanic fish acquisition of two Mayan sites. *Journal of Archaeological Science*: Reports 8: 116-120.

Kaitaniemi P, Lintunen A, Sievänen R. 2020. Power-law estimation of branch growth. *Ecological Modelling* 416.

Kennel P, Tramon M, Barbier N, Vincent G. 2013. Canopy height model characteristics derived from airbone laser scanning and its effectiveness in discriminating various tropical moist forest types. *International Journal of Remote Sensing* 34 (24): 8917-8935.

Khumalo LW, Majoko L, Read JS, Nucbe I. 2002. Characterization of some underutilized vegetable oils and their evaluation as starting materials for Lipase-catalyzed production of cocoa butter equivalents. *Industrial Crops and Products* 16: 237-244.

Khumalo-Mbonambi M, Inderpal LA, Karodia AM. 2014. An Evaluation of the Business Practices of Entrepreneurs of UMkhanyakude District Municipality. *Australian Journal of Business and Management Research* 4 (2), 15.

Kleynhans EPJ, Coetzee C. 2019. Assessment of Financial Conditions of South African Municipalities: A Unique Model for KwaZulu-Natal. *Southern African Business Review* 23:1-25.

Koffi CK, Lourme-Ruiz A, Djoudi H, Bouquet E, Dury S, Gautier D. 2020. The contributions of wild tree resources to food and nutrition security in sub-Saharan African drylands: a review of the pathways and beneficiaries. *International Forestry Review* 2020 (1): 64.

Komane BM, Olivier EI, Viljoen AM. 2011. Trichilia emetica (Meliaceae) – A review of traditional uses, biological activities and phytochemistry. *Phytochemistry Letters* 4(1): 1-9. Doi:10.1016/j.phytol.2010.11.002.

Kumar VVP, Srinivas NR. 2008. Application of allometry principles for the prediction of human pharmacokinetic parameters for irbesartan, a AT 1 receptor antagonist, from animal data. *European journal of drug metabolism and pharmacokinetics* 33 (4): 247-252.

Kuyah S, Dietz J, Muthuria C, Jamnadass R, Mwangi P, Coe R, Neufeldt H. 2012a. Allometric equations for estimating biomass in agricultural landscapes: Above ground biomass. *Agriculture Ecosystems and Environment* 158: 216-224.

Kuyah S, Dietz J, Muthuria C, Jamnadass R, Mwangi P, Coe R, Neufeldt H. 2012b. Allometric equations for estimating biomass in agricultural landscapes: Belowground biomass. *Agriculture Ecosystems and Environment* 158: 225-234.

Lehtonen A. 2005. Estimating foliage biomass in Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) plots. *Tree Physiology* 25 (7): 803-811.

Letouzey R. 1982. Manuel de botanique forestière. Afrique tropicale. Tome 1: botanique générale. Tome 2A: familles (1ère partie). Tome 2B: familles (2è partie).

Levick SR, Whiteside T, Loewensteiner DA, Rudge M, Bartolo R. 2021. Leveraging TLS as a calibration and validation tool for MLS and ULS mapping of savanna structure and biomass at landscape-scales. *Remote Sensing* 13 (2): 257.

Levinton JS. 2001. Genetics, paleontology, and macroevolution. *Cambridge University Press*.

Li JK. 2018. Cardiovascular allometry: analysis, methodology, and clinical applications. *Sex-Specific Analysis of Cardiovascular Function* 207-224.

Lovang U, Wildt-Persson T. 1998. Botanical pesticides: the effect of aqueous extracts of Melia azedarach and Trichilia emetica on selected pathogens of tomato, bean and maize. *Minor Field Studies - Swedish University of Agricultural Sciences, International Office (Sweden)* 1998(52): 22. Accessed May 14, 2021.

Lyman RL. 2018. Observations on the history of zooarchaeological quantitative units: why NISP, then MNI, then NISP again?. *Journal of Archaeological Science*: Reports 18: 43-50.

Mahmood I. 2018. Prediction of tissue to plasma concentration ratios of drugs in the rat from experimentally estimated volume of distribution: application of allometry. *Current drug metabolism* 19 (2): 155-164.

Malafronte N, Sanogo R, Vassallo A, De Tommasi N, Bifulco G, Dal Piaz F. 2013. Androstanes and pregnanes from Trichilia emetica ssp. suberosa J.J. de Wilde. *Phytochemistry* 96: 437-442. Doi:10.1016/j.phytochem.2013.09.019.

Maniatis D, Saint André L, Temmerman M, Malhi Y, Beeckman H. 2011. The potential of using xylarium wood samples for wood density calculations: a comparison of approaches for volume measurement. *iForest* 4, pp 150-159.

Mashile SP, Tshisikhawe MP, Masevhe NA. 2018. Indigenous fruit plants species of the Mapulana of Ehlanzeni district in Mpumalanga Province, South Africa. *South African Journal of Botany* 122 (2019): 180-183.

Mashungwa GN, Mmolotsi RM. 2007. Trichilia emetica Vahl. In: van der Vossen HAM, Mkamilo GS (eds). Plant Resources of Tropical Africa 14: Vegetable oils/Oléagineux. PROTA, Wageningen, Netherlands. [http://www.prota4u.org/search.asp], accessed 19 May 2021.

Matakala P, Maússe A, Macucule A. 2005. Mafurra, Trichilia emetica - Local indigenous knowledge, uses and agroforestry potential. *World Agroforestry Centre*- ICRAF/FAO Technical Report, Hamilton-Fynch, South Africa.

Matthews WS, Van Wyk AE, Van Rooyen N. 1999. Vegetation of the Sileza Nature Reserve and neighbouring areas, South Africa, and its importance in conserving the woody grasslands of the Maputaland Centre of Endemism. *Bothalia* 29 (1): 151-167.

McKenzie B. 1988. Guidelines for the sustained use of forests and forest products. A Workshop Report. Forest Biome Project, *FRD*: *CSIR*, Pretoria.

Mengich E, Macharia J, Mitloehner R, Too D, Muturi G. 2020. DIAMETER DISTRIBUTION OF INDIGENOUS TREES AS INDICATOR OF ADAPTED SPECIES IN SEMI-ARID RANGELANDS OF KENYA. *Journal of Tropical Forest Science* 32 (2): 144-153.

Mensah S, Veldtman R, Toit Bd, Kakaï R, Seifert T. 2016. Aboveground Biomass and Carbon in a South African Mistbelt Forest and the Relationships with Tree Species Diversity and Forest Structures. *Forests* 79 (7): 1-17.

Mensah S, Veldtman R, Seifert T. 2017. Allometric models for height and aboveground biomass of dominant tree species in South African Mistbelt forests. *Southern Forests*: *a Journal of Forest Science* 79:1, 19-30.

Mensah S, Pienaar O, Kunneke A, Toit Bd, Seydack A, Uhl E, Pretzsch H, Seifert T. 2018. Height-Diameter allometry in South Africa's indigenous high forests: Assessing generic models performance and function forms*. Forest Ecology and Management* 410.

Mizrahi Y, Nerd A, Sitrit Y. 2002. New fruits for arid climates. In: Janick J, Whipkey A (eds), *Trends in new crops and new uses*. ASHS Press, Alexandria. pp 378-384.

Mokany K, Raison RJ, Prokushkin AS. 2006. Critical analysis of root: shoot ratios in terrestrial biomes. *Global change biology* 12 (1): 84-96.

Molto Q, Rossi V, Blanc L. 2012. Error propagation in biomass estimation in tropical forests. *Methods in Ecology and Evolution* 4: 175-183.

Morgenthal TL, Kellner K, Van Rensburg L, Newby TS, Van der Merwe JPA. 2006. Vegetation and habitat types of the Umkhanyakude Node. *South African Journal of Botany* 72(1): 1-10.

Mors WB, Nascimento MC, Pereira BM, Pereira NA. 2000. Plant natural products active against snake bite–the molecular approach. *Phytochemistry* 55 (6): 627-642.

Mucina L, Von-Maltitz G, Geldenhuys C, Lawes M, Eeley H, Adie H, Vink D, Fleming G, Bailey C. 2003. Classification system for South African Indigenous Forests: An objective classification for the Department of Water Affairs and Forestry. *Department of Water Affairs and Forestry* 2003.

Mucina L, Rutherford MC. 2006. The vegetation of South Africa, Lesotho and Swaziland. Strelitzia 19. South African National Biodiversity Institute, Pretoria, ZA.

Mucina L. 2018. Vegetation Survey and Classification of Subtropical Forests of Southern Africa. Springer, 2018. ISBN 9783319678306.

Mugasha W, Eid T, Bollandsas M, Malimbwi E, Chamshama SA, Zahabu E, Katani JZ. 2013. Allometric models for prediction of above- and belowground biomass of trees in the miombo woodlands of Tanzania. *Forest Ecology and Management* 310: 87-101.

Murray C. 1927. A relationship between circumference and weight in trees and its bearing on branching angles. *The Journal of general physiology* 10 (5): 725-9.

Mpanza D, Govender P. 2017. Rural realities in service provision for substance abuse: a qualitative study in uMkhanyakude district, KwaZulu-Natal, South Africa. *South African Family Practice* 59 (3):110-115.

Mthembu A, Hlophe S. 2020. Building resilience to climate change in vulnerable communities: A case study of uMkhanyakude district municipality. *Town and Regional Planning* 77: 42-56.

Mwamba CK. 2006. Monkey orange: Strychnos cocculoides - Crops for the Future. Southampton Centre for Underutilised Crops, Southampton, UK.

Naidoo K, Gate KR, Mfeka-Nkabinde NG. 2020. An assessment of nutritional status in children of rural, northern KwaZulu-Natal province. *South African Family Practice* 62 (1): 1-7.

Nchimbi HY. 2020. Quantitative and qualitative assessment on the suitability of seed oil from water plant (Trichilia emetica) for soap making. *Saudi Journal of Biological Sciences* 27(11): 3161-3168.

Ngadze RT, Verkerk R, Nyanga LK, Fogliano V, Linnemann AR. 2017. Improvement of traditional processing of local monkey orange (*Strychnos* spp.) fruits to enhance nutrition security in Zimbabwe. *Food Security* 9: 621-633.

Ngadze RT. 2018. Value addition of Southern African monkey *orange (Strychnos spp.): composition, utilization and quality* (Doctoral dissertation, Wageningen University and Research).

Ngadze RT, Linnemann AR, Fogliano V, Verkerk R. 2019. Monkey orange fruit juice improves the nutritional quality of a maize-based diet. *Food research international* (Ottawa, Ont) 116: 870-877.

Ngemakwe NPH, Remize F, Thaoge ML, Sivakumar D. 2017. Phytochemical and nutritional properties of underutilised fruits in the southern African region. *South African Journal of Botany* 113: 137-149.

Ngomanda A, Laurier EON, Lebamba J, Moundounga Q, Gomat H, Mankou G, Loumeto J, Iponga D, Ditsouga F, Zinga R, Bobé K, Okouyi C, Nyangadouma R, Lépengué N. 2014. Site-specific versus pantropical allometric equations: Which option to estimate the biomass of a moist central African forest? *Forest Ecology and Management* 312: 1-9.

Nkosi NN, Mostert THC, Dzikiti S, Ntuli NR. 2020. Prioritization of indigenous fruit tree species with domestication and commercialization potential in KwaZulu-Natal, South Africa. *Genetic Resources & Crop Evolution* 67 (6): 1567.

Nyoka B, Chanyenga T, Mng'omba S, Akinnifesi F, Sagona W. 2015. Variation in growth and fruit yield of populations of Sclerocarya birrea (A. Rich.) Hochst. *Agroforestry Systems* 89 (3): 397-407.

Olson DM, Dinerstein E, Wikramanayake ED, Burgess ND, Powell GV, Underwood EC, D'amico JA, Itoua I, Strand HE, Morrison JC, Loucks CJ. 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth. A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *BioScience* 51 (11): 933-938.

Paladinić E, Vuletić D, Martinić I, Marjanović H, Indir K, Benko M, Novotny V. 2009. Forest biomass and sequestered carbon estimation according to main tree components on the forest stand scale. Periodicum Biologorum 111(4): 459-466.

Pearce S, Holland D. 1957. Randomized Branch Sampling for Estimating Fruit Number. *Biometrics* 13 (2): 127-130. Doi: 10.2307/2527796.

Pearson T, Brown S. 2005. Guide de mesure et de suivi du carbone dans les forêts et prairies herbeuses. *Winrock International*, 11-35.

Pérez-Piqueres A, Martínez-Alcántara B, Rodríguez-Carretero I, Canet R, Quiñones A. 2020. Estimating carbon fixation in fruit crops. In: Srivastava AK, Hu C (eds), *Diagnosis and Management of Nutrient Constraints*. *Fruit Crops* 2020. pp 67-76.

Peters SE. 1983. Postnatal development of gait behaviour and functional allometry in the domestic cat (Felis catus). *Journal of Zoology* 199 (4): 461-486.

Peters RH, Cloutier S, Dubé D, Evans A, Hastings P, Kaiser H, Kohn D, Sarwer-Foner B. 1988. The Allometry of the Weight of Fruit on Trees and Shrubs in Barbados. *Oecologia*, vol. 74, No. 4, pp 612-616.

Phiri D, Ackerman P, Wessels B, du Toit B, Johansson M, Säll H, Seifert T. 2015. Biomass equations for selected drought-tolerant eucalypts in South Africa. *Southern Forests: a Journal of Forest Science* 77(4): 255-262.

Picard N, Saint-André L, Henry M. 2012. *Manuel de construction d'équations allométriques pour l'estimation du volume et la biomasse des arbres: de la mesure de terrain à la prédiction*. Montpellier: CIRAD-FAO.

Picard N, Bosela FB, Rossi V. 2015. Reducing the error in biomass estimates strongly depends on model selection. *Annals of forest Science* 72 (6): 811-823.

Platt SG, Rainwater TR, Thorbjarnarson JB, Finger AG, Anderson TA, McMurry ST. 2009. Size estimation, morphometrics, sex ratio, sexual size dimorphism, and biomass of Morelet's crocodile in northern Belize. *Caribbean Journal of Science* 45 (1): 80-93.

Poojary MM, Passamonti P. 2020. Interesterification of mafura butter and camellia oil for cosmeceutical formulations: Chemical composition and physicochemical properties of products. *Industrial Crops & Products*: *147*.

Poorter H, Niklas KJ, Reich P, Oleksyn J, Poot P, Mommer L. 2011. Biomass allocation to leaves stems and roots: meta-analyses of interspecific variation and environmental control. *New Phytologist* (2012) 193: 30-50.

R DEVELOPMENT CORE TEAM. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

R DEVELOPMENT CORE TEAM. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Razzaq A, Hussain G, Rasul A, Xu J, Zhang Q, Malik SA, Anwar H, Aziz N, Braidy N, de Aguilar JLG, Wei W, Li J, Li X. 2020. Strychnos nux-vomica L. seed preparation promotes functional recovery and attenuates oxidative stress in a mouse model of sciatic nerve crush injury. *BMC Complementary Medicine and Therapies* 20 (1): 1-11.

Reitz EJ, Quitmyer IR, Stephen HH, Scudder SJ, Wing ES. 1987. Application of Allometry to Zooarchaeology. *American Antiquity* vol. 52, Issue 2, pp 304-317.

Rodrigues S, de Brito ES, Silva EO. 2018. Maboque/Monkey Orange–Strychnos spinosa. In: Rodrigues S, de Brito ES, Silva EO (eds), *Exotic Fruits*. Academic Press: reference guide. pp 293-296.

Rondeux J. 1999. La mesure des arbres et des peuplements forestiers (2nd edn). Gembloux: Les Presses Agronomiques de Gembloux. ISBN : 2-87016-060-7.

Rudge ML, Levick SR, Bartolo RE, Erskine PD. 2021. Modelling the Diameter Distribution of Savanna Trees with Drone-Based LiDAR. *Remote Sensing* 13 (7): 1266.

Ruff C. 1987. Structural allometry of the femur and tibia in Hominoidea and Macaca. *Folia Primatologica* 48 (1-2): 9-49.

Ruff CB, Walker A, Teaford MF. 1989. Body mass, sexual dimorphism and femoral proportions of Proconsul from Rusinga and Mfangano Islands, Kenya. *Journal of Human Evolution* 18 (6): 515-536.

Rupšys P. 2016. New insights into tree height distribution based on mixed effects univariate diffusion processes. *PloS One* 11(12), e0168507.

Rutherford MC, Westfall RH. 1986. Biomes of southern Africa: an objective categorization. *Memoirs of the Botanical Survey of South Africa* 1986.

Ryan CM, Williams M, Grace J. 2011. Above- and Belowground Carbon Stocks in a Miombo Woodland Landscape of Mozambique. *Biotropica* 43(4): 423–432.

Salmona J, Banks M, Ralantoharijaona TN, Rasolondraibe E, Zaranaina R, Rakotonanahary A, Wohlhauser S, Sewal BJ, Chikhi L. 2015. The value of the spineless monkey orange tree (Strychnos madagascariensis) for conservation of northern sportive lemurs (Lepi lemurmilanoii and L. ankaranensis). *Madagascar Conservation & Development* 10 (2): 53-59.

Sanquetta CR, Corte AP, da Silva F. 2011. Biomass expansion factor and root-to-shoot ratio for Pinus in Brazil. *Carbon Balance and Management* 6 (1): 1-8.

Savadogo P, Tigabu M, Sawadogo L, Odén PC. 2007. Woody species composition, structure and diversity of vegetation patches of a Sudanian savanna in Burkina Faso. *Bois et forêts des tropiques* 294 (4): 5-20.

Saya JM, Ruijter E, Orru RVA. 2019. Total Synthesis of Aspidosperma and Strychnos Alkaloids through Indole Dearomatization. *Chemistry - A European Journal* 25 (38): 8916-8935.

Schoeman S, Faber M, Adams V, Smuts C, Ford-Ngomane N, Laubscher J, Dhansay M. 2010. Adverse social, nutrition and health conditions in rural districts of KwaZulu-Natal and the Eastern Cape provinces, South Africa. *South African journal of clinical nutrition* 23 (3).

SDF (Spatial Development Framework). 2018. Umhlabuyalingana Municipality Draft Spatial Development Framework 2018. Available at http://www.umhlabuyalingana.gov.za/docs/reports/20180404/UMHLABUYALINGANA_SDF_2018_.pdf [accessed 10 August 2021].

Semenov VA, Samultsev DO, Krivdin LB. 2020. 1H and 13C NMR spectra of Strychnos alkaloids: Selected NMR updates. *International Journal of Quantum Chemistry* 120 (19): 1-17.

Sershen, Perumal A, Varghese B, Govender P, Ramdhani S, Berjak P. 2014. Effects of elevated temperatures on germination and subsequent seedling vigour in recalcitrant Trichilia emetica seeds. *South African Journal of Botany* 90:153-162. Doi:10.1016/j.sajb.2013.11.005.

Shai KN, Ncama K, Ndhlovu PT, Struwig M, Aremu AO. 2020. An Exploratory Study on the Diverse Uses and Benefits of Locally-Sourced Fruit Species in Three Villages of Mpumalanga Province, South Africa. *Foods* 9 (11).

Shirima DD, Munishi PK, Lewis SL, Burgess ND, Marshall AR, Balmford A, Zahabu EM. 2011. Carbon storage, structure and composition of miombo woodlands in Tanzania's Eastern Arc Mountains. *African Journal of Ecology* 49 (3): 332-342.

Sitrit Y, Loison S, Ninio R, Dishon E, Bar E, Lewinsohn E, Mizrahi Y. 2003. Characterization of monkey orange (Strychnos spinosa Lam.), a potential new crop for arid regions. *Journal of Agricultural and Food Chemistry* 51 (21): 6256-6260.

Socha J, Wezyk P. 2007. Allometric equations for estimating the foliage biomass of Scots pine. *European Journal of Forest Research* 126: 263-270.

Sofo A, Nuzzo V, Palese AM, Xiloyannis C, Celano G, Zukowskyj P, Dichio B. 2005. Net CO2 storage in Mediterranean olive and peach orchards. *Scientia Horticulturae* 107: 17–24.

Steinman AD, Lamberti GA, Leavitt PR, Uzarski DG. 2017. Biomass and Pigments of Benthic Algae. In: Hauer FR, Lamberti GA (eds), *Methods in Stream Ecology*. Academic Press. Vol. 1 (3rd edn). pp 223-241.

Sulieman AME, Mariod AA. 2019. Domestication of Indigenous Fruit Trees. In: Mariod A. (eds), *Wild Fruits: Composition, Nutritional Value and Products*. Springer, Cham.

Syampungani S, Geldenhuys CJ, Chirwa PW. 2016. Regeneration dynamics of miombo woodland in response to different anthropogenic disturbances: forest characterisation for sustainable management. *Agroforestry systems* 90 (4): 563-576.

Szalay FS. 1991. The unresolved world between taxonomy and population biology: what is, and what is not, macroevolution?: Genetics, Paleontology, and Macroevolution. By Jeffrey Levinton (1988). New York: Cambridge University Press. ISBN 0-521-24933-3. *Journal of human evolution* 20 (3): 271-280.

Thieren E, Van-Neer W. 2016. Scutes for sturgeon size reconstruction: traditional and geometric morphometric techniques applied to Acipenser sturio and A. oxyrinchus. *Archaeofauna* 25 (1).

Tsopgni WDT, Azébazé AGB, Happi GM, Frese M, Sewald N, Mbobda ASW, Kouam SF, Lenta BN, Stammler HG, Neumann B. 2019. Chemical constituents from the bark of the Cameroonian mahogany Trichilia emetica Vahl (Meliaceae). *Phytochemistry Letters* 33: 49-54. Doi:10.1016/j.phytol.2019.07.009.

van Rayne KK, Adebo OA, Ngobese NZ. 2020. Nutritional and Physicochemical Characterization of Strychnos madagascariensis Poir (Black Monkey Orange) Seeds as a Potential Food Source. *Foods* 9 (1060): 1060.

Vermaak I, Kamatou GPP, Komane-Mofokeng B, Viljoen AM, Beckett K. 2011. African seed oils of commercial importance — Cosmetic applications. *South African Journal of Botany* 77(4): 920-933. Doi:10.1016/j.sajb.2011.07.003.

Vieilledent G, Vaudry R, Andriamanohisoa SF, Rakotonarivo OS, Randrianasolo HZ. 2012. A universal approach to estimate biomass and carbon stock in tropical forests using generic allometric models. *Ecological Applications* 22 (2), pp 572-583.

Vlok J, Euston-Brown D. 2002. Description of the vegetation types in the thicket biome. Terrestrial Ecology Research Unit Report (unpublished), STEP Project.

Vlok J, Euston-Brown D, Cowling R. 2003. Acocks' Valley Bushveld 50 years on: New perspectives on the delimitation, characterization and origin of subtropical thicket vegetation. *South African Journal of Botany* 69 (1): 27-51.

Werner P, Prior L. 2013. Demography and growth of subadult savanna trees: Interactions of life history, size, fire season, and grassy understory. *Ecological Monographs* 83 (1): 67-93.

White F. 1983. The vegetation of Africa. Natural Resources Research. Paris, UNESCO Press.

Wibbe ML, Blanke MM, Lenz F. 1993. Effect of fruiting on carbon budgets of apple tree canopies. *Trees - Structure and Function* 8: 56–60.

Wickham H. 2016. Ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York.

Wu T, Wang Y, Yu C, Chiarawipa R, Zhang X, Han Z, Wu L. 2012. Carbon Sequestration by Fruit Trees - Chinese Apple Orchards as an Example. *PLoS ONE* 7(6): e38883.

Zimudzi C, Chapano C. 2016. Diversity, population structure, and above ground biomass in woody species on Ngomakurira Mountain, Domboshawa, Zimbabwe. *International Journal of Biodiversity* 2016: 1-11.

……

ANNEXURES

Annexure 1: Ethical clearance certificate

UNIVERSITY OF ZULULAND
RESEARCH ETHICS COMMITTEE
(Reg No: UZREC 171110-030)

RESEARCH & INNOVATION
Website: http://www.unizulu.ac.za
Private Bag X1001
KwaDlangezwa 3886
Tel: 035 902 6273
Email: ViljoenD@unizulu.ac.za

ETHICAL CLEARANCE CERTIFICATE

Certificate Number	**UZREC 171110-030 PGD 2021/25**							
Project Title	**Fruit-based allometry of Strychnos spinosa, S. madagascariensis and Trichilia emetica in the savanna woodlands of Umhlabuyalingana municipality, KwaZulu-Natal province**							
Principal Researcher/ Investigator	A.L Akweni							
Supervisor and Co-supervisor	Prof G.E Zharare							
Department	Agriculture							
Faculty	Science and Agriculture							
Type of Risk	Low Risk – Desktop, field work or laboratory							
Nature of Project	Honours/4th Year		Master's		**Doctoral**	**x**	Departmental	

The University of Zululand's Research Ethics Committee (UZREC) hereby gives ethical approval in respect of the undertakings contained in the above-mentioned project. The Researcher may therefore commence with data collection as from the date of this Certificate, using the certificate number indicated above.

Special conditions:

(1) This certificate is valid for 1 year from the date of issue.
(2) Principal researcher must provide an annual report to the UZREC in the prescribed format [due date-17 March 2022]
(3) Principal researcher must submit a report at the end of project in respect of ethical compliance.
(4) The UZREC must be informed immediately of any material change in the conditions or undertakings mentioned in the documents that were presented to the meeting.

The UZREC wishes the researcher well in conducting research.

pp

Professor Mashupye R. Kgaphola
University Research Ethics Committee
Deputy Vice-Chancellor: Research & Innovation

17 March 2021

CHAIRPERSON
UNIVERSITY OF ZULULAND RESEARC
ETHICS COMMITTEE (UZREC)
REG NO: UZREC 171110-30
-03-
RESEARCH & INNOVATION OFFICE

Annexure 2: Proof-editing certificate

ChizzyfolUleanya EDITING AND FORMATTING

Email:chinazauleanya@yahoo.com

02 October 2021

Sir / Ma,

To Whom It May Concern

RE: Confirmation of Article Editing for Arindo Lukawu Akweni

This letter serves as a confirmation that I have edited and proof-read Arindo Lukawu Akweni's research article titled '***Fruit-based allometry of Strychnos madagascariensis, S. spinosa, and Trichilia emetica in the savanna woodlands of the Umhlabuyalingana municipality, KwaZulu-Natal, South Africa.'*** The article is well written and its structure is well organised.

Yours sincerely

Chinaza Uleanya

(Editor)

B.A.Ed English

Lagos State University, Nigeria.

Mobile: +27788884942

Email: chinazauleanya@yahoo.com

Annexure 3: Dendrometric dataset used to calibrate the fruit-based allometric equations proposed in this study (in chapter 4). The tree ID number (**ID**), the name of the species, the diameter at breast height (**D**, in cm), the canopy diameter (**Dc**, in cm), the height (**H**, in m), the number of fruits hanged on the tree (**Nft**), the number of fruits fallen on the ground (**Nfd**), the total number of fruits of the tree (**NFT**), the mean fruit-diameter of sampled fruits (**Df**, in cm), the mean fresh biomass of sampled fruits of the tree (**Bf**, in g), and the total fresh fruit biomass of the tree (**AGfB**, in kg) are given for each tree.

.

N°	ID	Species	D	Dc	H	Nft	Nfd	NFT	Df	Bf	AGfB
1	1	*Strychnos_madagascariensis*	27.07	1000.00	4.80	94	62	156	9.13	451.68	**70.46137**
2	2	*Strychnos_madagascariensis*	14.97	620.00	4.30	58	1	59	8.38	344.94	**20.35130**
3	3	*Strychnos_madagascariensis*	17.20	599.00	4.25	86	11	97	7.84	270.05	**26.19463**
4	4	*Strychnos_madagascariensis*	15.61	798.00	2.86	71	16	87	8.05	359.42	**31.26928**
5	5	*Strychnos_madagascariensis*	9.24	363.00	3.80	46	6	52	7.91	331.77	**17.25183**
6	6	*Strychnos_madagascariensis*	15.29	593.00	4.90	13	58	71	8.34	398.75	**28.31103**
7	7	*Strychnos_madagascariensis*	18.47	802.00	4.45	70	38	108	8.10	347.01	**37.47708**
8	8	*Strychnos_madagascariensis*	33.12	890.00	5.40	89	61	150	8.34	331.78	**49.76633**
9	9	*Strychnos_madagascariensis*	2.26	271.00	2.89	6	1	7	8.50	519.08	**3.63356**
10	10	*Strychnos_madagascariensis*	20.38	580.00	5.71	75	18	93	7.80	349.76	**32.52768**
11	13	*Strychnos_madagascariensis*	27.07	860.00	5.66	81	33	114	8.88	410.69	**46.81836**
12	14	*Strychnos_madagascariensis*	16.24	580.00	4.10	22	11	33	10.45	612.93	**20.22669**
13	15	*Strychnos_madagascariensis*	23.89	713.00	5.61	99	19	118	7.90	354.36	**41.81448**
14	16	*Strychnos_madagascariensis*	21.02	506.00	5.80	77	8	85	7.70	344.22	**29.25870**
15	17	*Strychnos_madagascariensis*	15.64	614.00	4.01	54	21	75	8.10	289.01	**21.67575**
16	18	*Strychnos_madagascariensis*	17.52	698.00	5.32	61	34	95	7.57	240.97	**22.89248**
17	19	*Strychnos_madagascariensis*	13.54	311.00	3.70	20	8	28	8.10	530.13	**14.84364**
18	20	*Strychnos_madagascariensis*	16.24	413.00	4.61	55	3	58	9.10	545.92	**31.66336**
19	21	*Strychnos_madagascariensis*	25.48	838.00	5.70	156	103	259	7.80	290.07	**75.12766**
20	27	*Strychnos_madagascariensis*	10.19	508.00	3.80	44	7	51	8.20	331.22	**16.89222**
21	41	*Strychnos_madagascariensis*	20.70	885.00	5.47	73	12	85	7.01	335.09	**28.48265**

Continuation of annexure 3

N°	ID	Species	D	Dc	H	Nft	Nfd	NFT	Df	Bf	AGfB
22	42	*Strychnos_madagascariensis*	13.38	842.00	5.02	42	13	55	7.05	340.74	**18.74070**
23	43	*Strychnos_madagascariensis*	17.20	579.00	5.10	57	14	71	7.41	321.00	**22.79100**
24	61	*Strychnos_madagascariensis*	21.97	744.50	6.20	91	4	95	9.30	429.78	**40.82910**
25	63	*Strychnos_madagascariensis*	5.13	345.00	2.83	17	1	18	7.60	340.95	**6.13710**
26	67	*Strychnos_madagascariensis*	5.89	410.00	2.85	15	1	16	8.20	459.27	**7.34832**
27	68	*Strychnos_madagascariensis*	4.78	321.00	2.66	15	1	16	8.07	444.77	**7.11632**
28	69	*Strychnos_madagascariensis*	7.32	360.90	3.99	19	1	20	7.90	361.66	**7.23320**
29	70	*Strychnos_madagascariensis*	3.28	297.20	3.16	8	3	11	8.40	514.00	**5.65400**
30	71	*Strychnos_madagascariensis*	4.54	332.00	2.97	15	5	20	8.00	436.01	**8.72020**
31	72	*Strychnos_madagascariensis*	5.92	423.90	3.20	18	3	21	8.80	429.45	**9.01845**
32	73	*Strychnos_madagascariensis*	6.41	397.00	3.37	21	2	23	7.65	349.91	**8.04793**
33	74	*Strychnos_madagascariensis*	7.83	327.90	3.50	22	3	25	8.50	419.04	**10.47600**
34	75	*Strychnos_madagascariensis*	8.41	357.00	3.65	32	5	37	8.20	406.45	**15.03865**
35	76	*Strychnos_madagascariensis*	9.82	382.00	3.91	31	7	38	8.09	421.08	**16.00104**
36	77	*Strychnos_madagascariensis*	11.49	429.00	4.21	37	6	43	8.40	465.07	**19.99801**
37	78	*Strychnos_madagascariensis*	12.30	456.00	4.60	42	5	47	8.70	445.27	**20.92769**
38	79	*Strychnos_madagascariensis*	13.69	502.00	4.92	47	6	53	8.40	448.33	**23.76149**
39	80	*Strychnos_madagascariensis*	8.92	360.00	3.50	34	4	38	7.90	427.04	**16.22752**
40	62	*Strychnos_madagascariensis*	30.25	889.00	5.60	109	58	167	8.60	432.25	**72.18575**
41	11	*Strychnos_spinosa*	9.94	252.00	3.29	17	24	41	8.70	371.03	**15.21223**
42	12	*Strychnos_spinosa*	17.20	509.00	4.03	29	15	44	10.54	787.30	**34.64126**
43	22	*Strychnos_spinosa*	14.01	289.00	4.40	43	12	55	8.52	468.57	**25.77130**
44	23	*Strychnos_spinosa*	20.06	809.00	5.45	67	13	80	8.10	428.18	**34.25418**
45	24	*Strychnos_spinosa*	14.01	412.00	4.25	32	13	45	9.01	559.78	**25.19010**
46	25	*Strychnos_spinosa*	10.83	278.00	4.64	33	6	39	8.98	567.41	**22.12899**
47	26	*Strychnos_spinosa*	10.19	551.00	3.60	41	11	52	8.60	327.41	**17.02532**

Continuation of annexure 3

N°	ID	Species	D	Dc	H	Nft	Nfd	NFT	Df	Bf	AGfB
48	28	*Strychnos_spinosa*	12.10	657.00	4.55	38	5	43	8.68	397.44	**17.09003**
49	29	*Strychnos_spinosa*	16.37	458.00	4.21	32	8	40	8.50	530.87	**21.23480**
50	30	*Strychnos_spinosa*	14.97	450.00	5.05	44	13	57	9.80	612.62	**34.91953**
51	31	*Strychnos_spinosa*	10.19	329.00	3.17	38	14	52	8.30	334.29	**17.38308**
52	32	*Strychnos_spinosa*	14.33	560.00	4.10	45	14	59	8.22	396.60	**23.39952**
53	33	*Strychnos_spinosa*	10.51	460.00	3.34	40	11	51	8.10	362.90	**18.50790**
54	34	*Strychnos_spinosa*	7.64	300.00	2.98	50	1	51	6.87	264.02	**13.46519**
55	35	*Strychnos_spinosa*	7.48	377.00	3.11	21	4	25	7.10	318.14	**7.95350**
56	36	*Strychnos_spinosa*	7.93	423.00	2.85	33	1	34	8.00	435.23	**14.79782**
57	37	*Strychnos_spinosa*	10.16	328.00	3.29	15	9	24	9.00	544.00	**13.05588**
58	38	*Strychnos_spinosa*	2.87	226.00	2.49	6	1	7	8.80	526.24	**3.68368**
59	39	*Strychnos_spinosa*	3.82	175.00	2.63	5	1	6	8.20	519.98	**3.11988**
60	40	*Strychnos_spinosa*	5.73	211.00	3.72	14	1	15	8.10	478.35	**7.17525**
61	44	*Strychnos_spinosa*	14.14	458.00	4.27	41	33	74	7.13	273.20	**20.21703**
62	45	*Strychnos_spinosa*	14.33	395.00	4.63	41	9	50	8.97	543.18	**27.15917**
63	46	*Strychnos_spinosa*	14.65	617.00	4.51	39	12	51	8.10	397.13	**20.25363**
64	47	*Strychnos_spinosa*	11.78	323.00	4.13	41	9	50	8.00	447.78	**22.38900**
65	48	*Strychnos_spinosa*	20.38	843.00	5.70	70	7	77	7.40	421.14	**32.42778**
66	49	*Strychnos_spinosa*	13.06	279.00	3.94	32	9	41	9.10	494.69	**20.28229**
67	50	*Strychnos_spinosa*	22.93	978.00	5.87	93	27	120	7.63	268.15	**32.17776**
68	51	*Strychnos_spinosa*	11.46	352.00	4.61	40	21	61	7.80	305.53	**18.63713**
69	52	*Strychnos_spinosa*	10.67	560.00	3.92	23	1	24	9.55	723.74	**17.36964**
70	53	*Strychnos_spinosa*	11.15	449.00	3.40	60	6	66	8.40	517.49	**34.15434**
71	54	*Strychnos_spinosa*	6.69	199.20	2.54	16	4	20	8.10	330.32	**6.60640**
72	55	*Strychnos_spinosa*	7.90	201.70	2.49	17	7	24	7.75	335.67	**8.05608**
73	56	*Strychnos_spinosa*	9.24	311.00	2.60	28	9	37	7.70	360.08	**13.32296**

Continuation and ending of annexure 3

N°	ID	Species	D	Dc	H	Nft	Nfd	NFT	Df	Bf	AGfB
74	57	*Strychnos_spinosa*	15.89	346.50	2.99	31	1	32	9.20	642.99	**20.57568**
75	58	*Strychnos_spinosa*	9.87	430.20	3.01	48	8	56	8.28	439.66	**24.62096**
76	59	*Strychnos_spinosa*	6.05	489.00	4.17	18	10	28	9.10	474.10	**13.27480**
77	60	*Strychnos_spinosa*	7.83	364.10	2.90	20	4	24	8.10	399.63	**9.59100**
78	65	*Strychnos_spinosa*	22.29	530.00	5.20	91	30	121	8.60	401.28	**48.55488**
79	64	*Strychnos_spinosa*	26.11	774.00	5.15	115	13	128	8.20	443.36	**56.75008**
80	66	*Strychnos_spinosa*	21.97	850.00	5.60	84	16	100	7.90	370.43	**37.04300**