RELATING PLANT MORPHOLOGICAL TRAITS TO UPROOTING RESISTANCE IN EROSION CONTROL; A CASE STUDY IN NGUZU-EDDA, EBONYI STATE

BY

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CERTIFICATION

I certify that this work **"Relating Plant Morphological Traits to Uprooting Resistance in Erosion Control; a Case study of Nguzu-Edda in Ebonyi State"** was carried out by **Stanley Aloh Nwite (20124766368)** in partial fulfillment for the award of the degree of Master of Engineering (M.Eng) degree in Civil Engineering (Water Resources Engineering) of the Federal University of Technology Owerri.

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DEDICATION

To my late father;

Mr. Ali Nwite Ukpabi.

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NOTATIONS

D: Denotes stem basal diameter at the root-shoot junction.

H: Denotes Plant height.

DBH: Denotes diameter at Breast Height.

DW_R: Denotes total root dry weight.

DW_{R1}: Denotes tap root dry weight

L_R: Denotes total root length.

L_{R1}: Denotes length of the tap root.

V: Denotes total root system volume.

F_{MAX}: Denotes maximum force reached before plant uprooting.

σ_{MAX}: Denotes critical stress calculated as the ratio of F_{MAX} to plant basal cross-sectional area.

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ABSTRACT

The strength with which a plant resists uprooting in form of erosion is influenced by a number of morphological traits such as root form, the proportion of fine lateral roots, the stem basal diameter and the root biomass. However, it is unknown exactly what characteristics best promote plant stability. Few works have been done in this regard. This study relates plant morphological traits with resistance to uprooting by erosion. The case study selected for this research is the eroded land of Nguzu Edda in Ebonyi State, South Eastern-Nigeria where soils are subjected to harsh water erosion resulting in concentrated flows uprooting small plants. Several lateral uprooting tests were carried out to determine the uprooting forces for twelve plant species. In addition, measurements of above ground / underground traits of juvenile plants growing in the case study area were also carried out. Statistical analytical methods such as Analysis of Variance, Discriminant Analysis, Multiple range tests, multiple regressions were employed in the investigation. From results of analysis, plant maximum uprooting force ,F_{MAX}, was found to have a linear positive relationship with stem basal diameter, D, for all the species. The twelve (12) species studied were classified into two resistance groups based on their resistance to uprooting. The resistance group consisting of plant species such as *Oxytenthera abyssinica*(bamboo), *Vernonia amygdalina* (bitter leaf), *Milicia excelsa(*African Teak) associated with high values of root slenderness ratio (21.43 , 71.5,72.0), relative root volume {0.62,0.5,0.22}cm^3/cm, relative root dry weight {0.36,0.28,0.11} g/cm, percentage tap root dry weight{0.15,0.50,0.88}, root density{0.58,0.56,0.50}g/cm^3;low values of specific root length {3.38, 3.59 ,3.04}cm/g and low values of percentage fine root{45.5,36.0,42.0}% were most suitable as they yielded high resistance to uprooting. The relationship between plant resistance to uprooting and morphological traits were found to be non linear in nature for both resistance groups irrespective of growth form. Hence, it is recommended that those plant species with high resistance to uprooting are suitable for use in erosion mitigation, flood control and land reclamation. Also hybrids and clones of plants with desirable traits of high values of root slenderness ratio, relative root dry weight, percentage tap root dry weight, root density and low values of specific root length and percentage fine roots are suitable for breeding as vegetation to mitigate erosion, control flood and reclaim land. The findings of this research will be beneficial to those using vegetation to mitigate erosion and control flood.

Keywords: Plant traits, lateral uprooting, Uprooting resistance, Erosion, Statistical Analysis.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Plant morphological traits such as root form, tap root length, the proportion of fine lateral roots, the stem basal diameter, stem biomass and root biomass have dominant influence on uprooting resistance. However it is unknown exactly which of these characteristics best promote plant stability. It is important to identify characteristics contributing to plant stability. Such knowledge can be incorporated into breeding techniques and the development of clones with an increased mechanical stability which will be of great value to control erosion on exposed site with poor soil.

In Nguzu-Edda catchment of Afikpo South Local Government Area of Ebonyi State South-East Nigeria, soils are subjected to harsh water erosion that can result in concentrated flows uprooting small plants. Evaluating and predicting plant resistance to uprooting from simple plant traits is therefore highly important so that the most efficient plant strategy for future restoration of eroded slopes can be defined.

Anchorage failure is a problem in a wide range of plants growing in Nguzu – Edda erosion site of Afikpo in Ebonyi State; South-East, Nigeria. The site is faced with erosion menace, most notably cereals and timber trees and can result in significant economic losses.

1.2 Statement of Problem

In Nguzu-Edda catchment of Afikpo South Local Government Area of Ebonyi State South-East Nigeria, soils are subjected to harsh water erosion leading to concentrated flows uprooting small plants. When a plant is pulled from the soil, force is transmitted to the root system, which will fail at a point determined by the strength of the root, the soil strength, soil bond and the strength of the roots themselves in tension (Ennos, 1990). Anchorage failure is a problem in a wide range of plants growing in Nguzu – Edda lands of Afikpo in Ebonyi state faced with erosion menace, most notably cereals and timber trees and can result in significant economic losses which includes: loss of soil and land; loss of economic trees; loss of productive farm land; threats to houses and threat to access road.

In non woody roots such failure generally occurs in proximal region of the roots. However, the role of both lateral roots and root hairs in the anchorage remains un-quantified. Therefore evaluating and predicting plant resistance to uprooting from simple plant traits is therefore highly important so that the most efficient plant strategy (structured vegetation) can be employed for future restoration of eroded land. This research work therefore looked at the morphological traits of plant species in the case study area with a view to relating such to the uprooting strength or resistance to erosion and identifying the most efficient plant strategy for future restoration of eroded slopes.

1.3 Objectives of Study

The major objective of this work is to relate plant morphological traits to uprooting resistance in erosion control using the case study of Nguzu Edda eroded land in Afikpo South Local Government Area of Ebonyi State; South East Nigeria. The specific objectives of this work are:

(i.) To carry out In-situ lateral uprooting test on different species of plant.

(ii.) To measure some morphological traits of those plants which include tap root length, the proportion of fine lateral roots, the stem basal diameter, stem biomass and root biomass.

(iii) To relate the morphological traits of the plant species to their uprooting resistance/anchorage strength.

(iv) To develop models relating plant species morphological traits and the uprooting resistance or anchorage strength.

(v.) To recommend plant species and morphological traits that favor bioengineering in erosion mitigation, flood control and land reclamation.

1.4 Significance of the Study

This research study deals mainly with determining the relationship between plant morphological traits and the uprooting resistance or anchorage strength of plants in the eroded Nguzu-Edda land in Afikpo South L.G.A; of Ebonyi State

In a nutshell, the relevance of this project work can be justified as it would;

(i.) Help in establishing the relationship between plants morphological traits and the uprooting resistance which can be applied in erosion mitigation, flood control and land reclamation.

(ii.) Provide the information to be used in planning, design and application of bioengineering in erosion mitigation, flood control and land reclamation in the eroded land of Nguzu-Edda or other similar erosion sites with similar vegetation, hydrological and soil geotechnical properties.

(iii.) Enhance the application of bioengineering in erosion mitigation, flood control and land reclamation by selecting plant species based on morphological traits that contribute significantly to uprooting resistance or anchorage strength.

1.5 Scope of the Study

The study area is Nguzu – Edda eroded land of Afikpo in Ebonyi state, South- East Nigeria. The relationship between plant morphological traits and uprooting resistance of some plant species was investigated.

The work employed in-situ lateral uprooting test on the selected species of plant and measuring the morphological traits of the uprooted plants. The force gauge of the in-situ lateral uprooting test equipment records the force applied prior to uprooting. The direction of application of the force is to be parallel to the slope of the ground surface housing the plant to mimic the natural uprooting force of erosion. The tap root lengths of the uprooted plants are measured. The number of lateral roots are also ascertained in each sample plant and noted. The basal shoot diameter in each tested plant is also measured and noted.

The scope of this work also includes the geotechnical study of the case study area and obtaining the hydrological data of the study area from the approved authorities.

The range of this work furthermore includes the review of related literature.

1.6 Limitations

In the in-situ lateral uprooting test, the force gauge used in determining the uprooting force is affected by the speed of tensioning which may vary from one test to the other unlike what is applicable when a wrench is employed; however efforts were made to regulate the speed of tensioning of the force gauge and properly define the direction of tensioning.

There was problem of sourcing information relating to the topic. There has been limited information relating to the knowledge and understanding of the relationship between plant morphological traits and plant resistance to uprooting by erosive forces which has not been very active as compared to that on other methods of mitigating erosion and flood control.

There was inadequate fund with which to readily travel; to secure certain advanced equipment.

CHAPTER TWO

LITERATURE REVIEW

2.1 Bioengineering

Bioengineering is the application of engineering design and technology to living systems. In terms of flash flood mitigation, it refers to the combination of biological, mechanical, and ecological concepts to reduce or control erosion, protect soil, and stabilize slopes using vegetation or a combination of vegetation and construction materials (Finney,1993).Bioengineering techniques used in combination with civil and social engineering measures can reduce the overall cost of landslide mitigation considerably. Bioengineering offers an environmentally friendly and highly cost and time effective solution to slope instability problems in mountainous and hilly areas and is a technique of choice to control soil erosion, slope failure, landslides, and debris flows, and thus ultimately to help minimize the occurrence of floods and flash floods.

One of the major differences between physical construction techniques and bioengineering is that physical structures provide immediate protection, whereas vegetation needs time to reach maximum strength. Thus the combination of physical and vegetative measures offers a combination of immediate and long-term protection, as well as mitigation of the ecologically damaging effects of some physical constructions.

There were a number of previous studies conducted with the aim of studying the influences of plant morphological traits to uprooting resistances of soil permeated with roots. Unfortunately, the study on lateral uprooting resistance as a contribution to shear resistance has regrettably received little attention (Mickovski et al., 2007). Therefore, lateral uprooting resistance has become the main subject of study throughout this work.

Stokes et al., (1996) conducted an experiment on the influences of architectural and anchorage efficiency of plant root systems on resistance to uprooting (due to lateral force) using artificial root models subjected to lateral force. Artificial model of root systems with different topologies and branching angles, made out of copper coated steel wire were developed for use in that study. Results from the study had successfully verified that root branching patterns can greatly influence the pullout resistance. Branched structures were found to be difficult to uproot at greater depths than those without branches due to the existence of the lateral roots in the soil-root composites.

By similar principle and several additional variations, Mickovski et al., (2007) conducted a study on the influences of material stiffness, branching pattern and soil matrix potential to resist pullout force. According to the study, it was discovered that the maximum pullout resistance of roots in sand was highly dependent on the material stiffness, root architecture and the pore water suction of the sand. In terms of root architecture, it was observed that the maximum pullout resistance increased in the order of tap, herringbone and dichotomous root pattern where dichotomous root pattern was shown to have the highest pullout resistance compared to other root patterns for all root and soil conditions. This is due to the existence and position of the lateral roots which is located at each of these root models. The deeper these lateral roots were placed, the greater the resistances produced.

2.2 The Effects of Vegetation on the Slope Stability

As shown in Figure2.1, the shear stress along the slope is converted into the pulling out force at the end of the slope (plane area). The roots in this area denote some resistance against this kind of force. Khalilnejad, (2012) stated that, this kind of resistance has an important role in the slope stability as the root protects the soil at the toe of the slope against the pulling out force. Roots reflect some kind of resistance against the slope failure by increasing the shear resistance directly (by tensile force in the roots) and indirectly by increasing the normal stress over the surface thus affecting the strength through Mohr-Coulomb criterion. In other words, the roots work as biological nails to stabilize the slope. Lined up to those prior studies, this research concerns with the influences of plants morphological traits to their uprooting resistances. Predictions of the anchorage abilities are made with a regard to plants morphological traits as the main point to be discussed. Moreover, this knowledge also can be incorporated into a breeding technique to produce good quality plant clones. The selection of suitable plant clones have high potential in soil bioengineering and will be of great economic value for controlling erosion in exposed sites with poor soils.

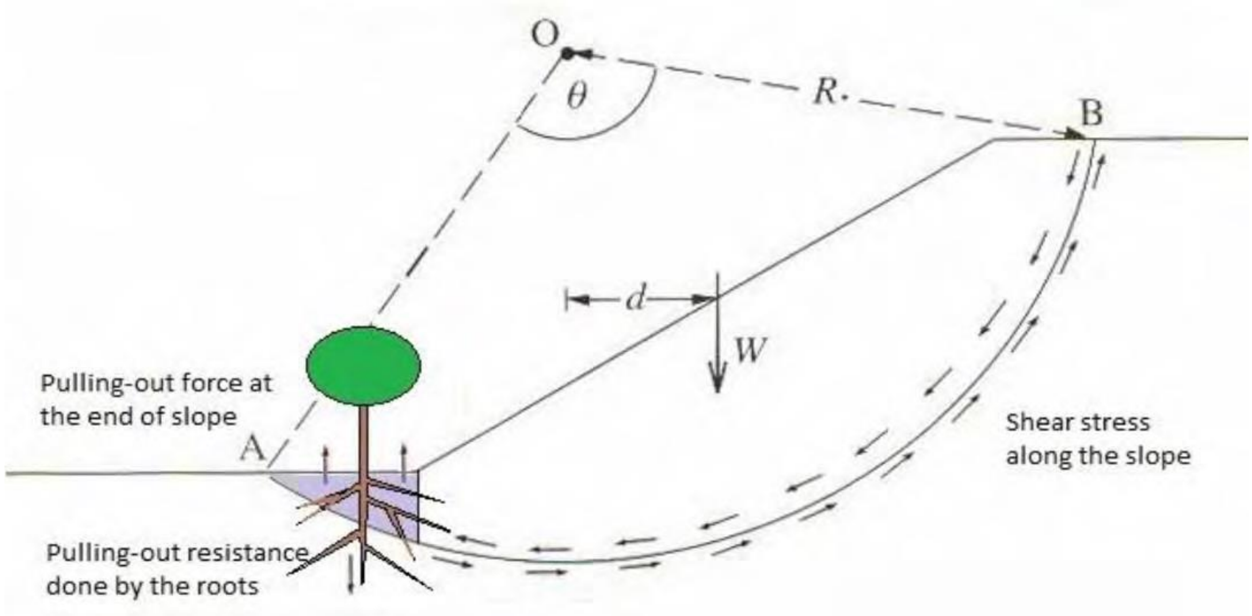

Figure 2.1: Stabilization of slope using Vegetations.

2.3 Hydrological Functions

Plants play a significant role in the hydrological cycle. Particularly, vegetation influences hydrological processes through effects on runoff; control of uptake, storage, return of water to the atmosphere and water quality.

The hydrological functions of vegetation can be summarized as follows:

(i.) Interception: The vegetation canopy intercepts raindrops and reduces their size and mechanical strength, thus protecting the soil from erosion caused by rain splash.

(ii.) Restraint: The dense network of coarse and fine roots physically binds and restrains soil particles in the ground, while the above ground portions filter sediment out of runoff.

(iii.) Absorption: Roots absorb surface water and underground water thus reducing the saturation level of soil and the concomitant risk of slope failure.

(iv.) Infiltration: Plants and their residues help to maintain soil porosity and permeability, thereby increasing retention and delaying the onset of runoff.

(v.) Evapo-transpiration: Vegetation transpires water absorbed through the roots and allows it to evaporate into the air at the plant surface.

(vi.) Surface runoff reduction: Stems and roots can reduce the velocity of surface runoff by increasing surface roughness.

2.4 Engineering Functions

Vegetation influences the stability of soil against erosion. The roles include:

(i.) Catching: Loose materials have a tendency to roll down a slope because of gravity and erosion, and this can be controlled by planting vegetation. The stems and roots can catch and hold loose material.

(ii.) Armoring: Some slopes are very water sensitive. They start moving and/or are easily liquefied when water falls on them. Vegetation can protect the surface from water infiltration and erosion by rain splash.

(iii.) Reinforcing: The shear strength of the soil can be increased by planting vegetation. The roots bind the grains of soil. The level of reinforcement depends on the nature of the roots.

(iv.) Supporting: Lateral earth pressure causes a lateral and outward movement of slope materials. Large and mature plants can provide support and prevent movement.

(v.) Anchoring: Layers with a tendency to slip over each other can be pinned to each other and the stable underlying layer by penetration of woody taproots from vegetation which functions as anchors.

(vi.) Draining: Water is the most common triggering factor for slope instability. Surface water drains away more easily in areas with dense rooted vegetation. Thus draining can be managed by planting small and dense rooted vegetation such as durva grass.

2.5 Plant Morphological Traits that Contribute to Uprooting Resistance

Over the past 20 years, many studies have been conducted on the mechanisms of plant anchorage contributing a great deal of information on the factors influencing anchorage strength. To withstand external constraints, plants must transfer the force into the soil via their roots. Plant anchorage depends on a combination of root system type and root system morphology (Dupuy et al., 2005b), soil properties (Ennos, 1990), and type of constraint, i.e. vertical uprooting or lateral loading (Ennos, 1993).

Several types of anchorage systems (plate, tap, coronal), growth forms (trees, shrubs, herbs), and type of soil or type of constraint (grazing, wind loading, hydrological forces) have been investigated. Experiments on physical and numerical models have made it easier to isolate the effects of a few root parameters on the entire plant's resistance to uprooting. Among plant traits, plant size (DBH, height, stem basal diameter, biomass), root system size (depth and lateral spread), root number, root length, and root branching are the most important traits related to plant anchorage. It has also been demonstrated that when subjected to mechanical stress such as wind loading, some species have higher numbers of roots and greater lateral root branching (Stokes et al., 1997; Mickovski and Ennos 2002), root length (Tamasi et al., 2005), lateral root basal cross-sectional area and root rigidity (Goodman and Ennos, 1997). These adaptations should improve the anchorage of plants. It should also be pointed out that other traits such as root stiffness (Crook and Ennos 1993; Goodman et al., 2001; Mickovski et al., 2007), changes in cell wall properties, i.e. lignin (Scippa et al., 2006) and cellulose (Genet et al., 2005), and root system asymmetry (Nicoll and Ray 1996; Mickovski and Ennos 2002) can also play a role in plant anchorage.

The objectives of most of the studies on plant anchorage carried out over the last 20 years were to gain information on the anchorage mechanics of a single species or to investigate the influence of one specific factor such as branching pattern, lateral roots, or root hairs on anchorage efficiency. To date, few studies have been conducted on large sets of species. Many of the factors related to anchorage, such as diameter, biomass, and root number, vary with regard to plant size and age. Consequently, the results available in the literature are often valid for one species and do not always enable relevant inter-specific comparison. Moreover, a large number of studies investigated trees, herbaceous dicots, and grasses but very few studies have focused on shrubby species, which are dominant species in eroded lands of Nguzu-Edda and which are often used for restoration purposes. To define the most efficient strategy for land management in the eroded land of Nguzu-Edda, it is important to be able to evaluate and predict the resistance to uprooting of young plants and seedlings planted for restoration purposes or that developed naturally on eroded lands. List of previous studies on plant anchorage carried out over the last 20 years is shown in Table 2.1.

Table 2.1: List of Morphological Traits Positively Correlated with Anchorage Strength according to the type of Study

Type of Material	Factors affecting anchorage	Key references
Live-material Temperate mature trees	DBH, Height, Stem mass, Root system depth, Root area, Root bending resistance	Crook and Ennos (1996), Cucchi et al. (2004), Mickovski and Ennos (2002).
Live-material Temperate Juvenile trees	Root volume, stem biomass, Tap-root length.	Karrenberg et al (2003), Khuder et al. (2007).
Live-material Tropical Trees.	DBH (Diameter at Breast Height)	Crook and Ennos (1998).
Live-material Tropical Herbaceous dicots	Stem basal diameter, Root biomass, Root bending resistance.	Ennos et al. (1993a), Goodman et al. (2001), Toukura et al (2006).
Live-material Tropical Grasses	Height, Lateral root spread, Biomass, Lateral root number, Lateral root volume, Root bending resistance.	Bailey et al. (2002), Crook and Ennos (1993), Ennos et al. (1993b), Mickovski et al (2005), Stokes et al (2007).
Live-material Aquatic Macrophytes.	Root number, Root area.	Schutten et al., (2005).
Physical model	Root system depth, Root length, Root branching, Root stiffness.	Mickovski et al., (2007), Stokes et al. (1996).
Numerical model	Root system type, Root system depth, Lateral root spread, Root number, Root diameter, Root branching.	Dupuy et al., (2005a,b).

Source: Burylo etal., 2009.

2.6 The Role of Root System Architecture in Promoting Anchorage against Uprooting Forces

The role played by lateral roots and root hairs in promoting plant anchorage and specifically resistance to uprooting forces cannot be over emphasized in Bioengineering practice and application and thus can be determined experimentally. Maximum strength of individual roots within a plant increases with plant age. The effects of roots in protecting the soil from being eroded can therefore not be neglected (Gray and Sotir, 1996). Roots affect properties of the soil, such as infiltration rate, aggregate stability, moisture content, shear strength and organic matter content, all of which control soil erosion rates to various degrees. One of the important mechanical characteristics of roots is that they are strong in tension. Soils, on the other hand, are strong in compression and weak in tension. A combined effect of soil and roots results in a reinforced soil. When shearing the soil, roots mobilize their tensile strength whereby shear stresses that develop in the soil matrix are transferred to the soil fibers via interface friction along the root length or via the tensile resistance of the roots. Uprooting is expected to occur in plants having a high shoot biomass and low root to shoot ratio (R: S). The magnitude of root reinforcement depends on morphological characteristics of the root system (e.g. root distribution with depth, root distribution over different root diameter classes), root tensile strengths, root tensile modulus values, the interface friction between roots and the soil and the orientation of roots to the principal direction of strain (Greenway, 1987).

Various designers have incorporated the geotechnical as well as ecological benefits of vegetation into water resource and slope stabilization projects, with comprehensive documentation dating back to the early part of the 20th century.

Schiectl and Stern (1997) provide an excellent review of design objectives and typical treatments for waterways bioengineering projects. Greenway (1987) reviews geomorphic factors influencing bioengineering design and discusses mechanisms and analysis tools related to reinforcement of soil by roots with a focus on slope and embankment sites. Specific attention is paid to the soil's resistance to root displacement and the effect of root's pull-out resistance to the normal load on the shear surface. By measuring the forces in a single root, as this root is displaced, we might better understand the forces involved in root reinforcement and be able to develop a database of plants that can be used in slope stabilization exhibiting outstanding root mechanical properties.

In uprooting tests on seedlings, resistance to uprooting could be resolved into series of events associated with the breakage of individual roots. When a plant is pulled from the soil, force is transmitted to the root system, which will fail at a point determined by the strength of the root, the soil strength, soil bond and the strength of the roots themselves in tension. In non woody roots such failure generally occurs in the proximal region of the roots (Ennos, 1993).

The role of both lateral and tap roots in the anchorage of a plant remains unquantified, although Stokes et al used wire model to predict that branching should increase uprooting resistance (Stokes et al., 1996). However, the rigid wire models are obviously not close mimics of non – woody roots and indeed models that bent during uprooting behaved differently.

In most plants a single force applied to stem will be transmitted to numerous roots either because of lateral branching or because of adventitious roots from the stem base. This allows more efficient transfer of the load to the soil because many narrow roots have a greater surface area than a single thick one (Ennos, 1993).

Quantifying the role of laterals and, more generally of root architecture on anchorage will allow a clearer understanding of the relative importance in determining the evolution of the diversity of root system form (Fitter,1999). It will provide the basic data from which to consider the potential for selection of crop plant resistance to uprooting.

2.6.1 Types of Root Systems

The crucial role of root systems in plant stability and survival has started to receive much attention only in the last twenty years. One obvious discouragement previously to investigating the growth and function of root systems was their variable form and their extensive branching, which complicate experimentation, especially since roots are covered by soil. In field conditions the root systems of plants are much more variable in form than their shoots. Considering their morphology, it is quite probable that the forces a plant must withstand could determine the shape of the root system. The simplest anchorage systems (Ennos, 1989) are the ones designed to resist only axial uprooting forces, such as might be caused by grazing or weeding.

(a.)Fibrous root systems, which are common in procumbent and climbing plants, have long roots that break, so that their tips do not contribute to anchorage, though they are optimal for weak soils. Short roots, in contrast, would be pulled out without mobilizing their full strength (Ennos, 1993). In these systems tension is transferred from the roots to the soil by the friction between them.

However, it is worth noting that the influence of the solid shape of roots on the uprooting resistance has never been studied. Mature self-supporting plants in contrast, have a range of root system types which must resist a more complicated set of forces, including overturning forces imposed by the wind. Such systems require at least one rigid element at the base of the stem to act as a lever (Ennos and Fitter, 1992). Most woody plants, for example, have a rigid element in their anchorage system to resist rotation moments.

(b.) Tap root systems resist rotation effectively, but longer and narrower taproots can easily break without mobilizing the full soil resistance, whereas shorter ones can easily rotate without mobilizing the full root strength. Other root systems, like (c.) The heart root system, where horizontal and vertical lateral roots develop from the base of the tree are the commonest type of root system in angiosperms and are usually found in large trees.

(d.)The plate root systems, on the other hand, often found in gymnosperms, become more efficient at large sizes, because the anchorage provided by the weight of the root-soil plate rises with the fourth power of the linear dimensions (compared to the third power for the taproots) (Ennos 1993, Nicoll*et al.*,1995, Stokes *et al.*,1995). Major lateral roots play a decisive role in resisting lateral loads imposed on plants. The chances of becoming a major root are greater for roots with a large diameter of primary xylem, or for roots with a special origin and position in the system that helps them to succeed in the battle for assimilate.

2.7 The Effects of Soil Properties on the Anchorage Strength of Plants

Plants growing on wet, gleyed or organic soils are more likely to be uprooted than those on better drained soil because of decreased soil shear strength (Kennedy, 1974). Saturation of otherwise freely draining soils coupled with strong runoff or strong wind can lead to widespread uprooting through decreased shear strength of the soil (Trousdell et al., 1965). When the root system is effective, soil to the root adhesion becomes the weak link in the system and uprooting occurs. Soil provides support in two ways:

(i.) By cohesive forces in the silts and clays,

(ii.) By frictional forces and shear strength in coarse-textured soil (Trousdell et al, 1965).

Wetness and saturation greatly reduce soil cohesion and shear strength; thereby increasing the possibility of uprooting (Pyatt, 1966). Soil properties that inhibits deep rooting , such as excessive stoniness, shallow bedrock, a clay rich horizon, a subsurface horizon of high bulk density, high water table, or toxicity in lower horizons, make plants more susceptible to uprooting (especially of vertical roots).

2.7.1 Theoretical Analysis of Anchorage

When an overturning force is applied to a cylindrical tap-root model with radius R, and underground length D_f, unconstrained at both ends, the failure can occur in two ways: either the tap breaks or it rotates through the soil. For the roots embedded in sand, engineering theory predicts that the rotation will occur around a point very close to, or at the root tip itself, while for the roots in agricultural soil the rotation will occur around a point approximately $D_f/2$ below the soil surface. If the root is effectively rigid, the soil will fail plastically and the theory of earth piles can be used to calculate the forces required. According to this theory (Broms 1964 a, b), the sand should resist overturning with a restoring moment Ms:

$$Ms = \gamma D_f^3 R k_p \quad (2.1)$$

Where, R is the model radius, γ is the unit weight of the sand, D_f is the model's underground length and k_p is the coefficient of passive earth pressure and is a function of the angle of internal friction.

$$k_p = (1+\sin\phi)/(1-\sin\phi) \quad (2.2)$$

The agricultural soil should resist the sideways motion of the root with a force dF acting on each small element of length dl.

$$dF = 18\tau R\,dl \quad (2.3)$$

Where τ is the shear strength of the cohesive soil .This should set up a restoring moment dM*:*

$$dM = 18\tau Rldl \quad (2.4)$$

Where l is the distance of the element from the centre of rotation. The total moment in agricultural soil M_a, resisting rotation is obtained by integrating dM over the half length of the rod for the models.

$$M_a=9 \tau RD_f^2 \quad (2.5)$$

The bending strength (Mb) of the tap-root is given by the equation:

$$M_b= \pi R^3\sigma/4 \quad (2.6)$$

Where σ is the breaking stress of the root material, and is proportional to the cube of root radius. Since the amount of material required to resist a given overturning force is minimized when the bending strength equals resistance to rotation in the respective soil type, $M_b=M_s$ and $M_b=M_a$.

For the roots in sand the optimal aspect ratio should be:

$$D_f^3/R^2 = (\pi\sigma/4\Upsilon k_p) \quad (2.7)$$

And for the roots in agricultural soil the optimal aspect ratio should be:

$$D_f^2/R^2= \pi\sigma/36\tau \quad (2.8)$$

Therefore for tap roots in sand one would predict that larger tap roots would be relatively shorter, whereas in agricultural soils the optimal shape should be independent of size.

2.8 Choice of appropriate Species

In general, it is best to use local species of vegetation in bioengineering as they are already adapted to the growing conditions, are more likely to be resistant to local diseases, are more readily available, and are likely to be a lower cost option. It can also be useful to choose species that can be used for other purposes as they mature, for example, providing fruit or with branches and leaves that can be used for fuel-wood, fodder, or other domestic purposes. This increases the benefit to local people and their acceptance of the measures (Allen, 1978).

Understanding of the pull-out resistance of a plant is useful in our assessment of its ability to sustain environmental stress and forces such as wind, landslide, mass movement and soil creeping. Major species that can be used for bioengineering purposes include different types of bamboo, Cane grass (*Saccharum officinarum*), Bahia grass (*Paspalum notatum*), Napier grass (*Pennisetum purpureum*), vetiver grass (*Vetiver zinzaniodes*), durva grass(*Cynodon dactylon*), Vernonia amygdalina, Azadirachta indica.

2.8.1 Bamboo Plant Species

Bamboo is not a tree, it is a giant grass. When bamboo is harvested, the root system is unharmed and healthy, ready to produce more shoots, just like a grass lawn. The rapid growth and the strong root systems make Bamboo particularly suited for soil protection. It is reported that a single bamboo plant can bind up to $6m^3$ of soil and research in China showed that soil erosion in a bamboo plantation is 4.7 times lower than in adjacent sweet potato crop land. Bamboo retains soil and lives on even after harvesting the stems. Bamboo is actually a species of giant woody grass. Certain timber bamboos have better tensile strength than iron or steel on a strength per weight basis. The use of bamboo plant in erosion mitigation is shown in Plate 2.1.

Plate 2.1 – The use of Bamboo plant in Erosion mitigation.

In Nigeria, there are two varieties of bamboo, viz; Bambusa vulgaris and Oxystenanthera abyssynicca. The Bambusa vulgaris attains a height of between 14–20 meter at maturity with a girth of about 20cm. The Oxystenanthera abyssynicca reaches between 8 – 12 meter at maturity. The two varieties grow naturally in the forests below River Niger. In Obowo Local Government Area of Imo state, Nigeria, there exist a local Community Based Organization (CBO) that specialized in using Bamboo and other local resources to check soil erosion in their locality. The vulnerability of their agricultural land to soil erosion has propelled them to develop initiatives towards addressing the problem. Today, their efforts are being emulated by other communities around. However, there may still be some institutions yet to be discovered that may be involved in the bamboo activities (Okafor et al., 1994).

2.8.2 Rattan Plant Species

Rattan and Bamboo are regarded as non – woody plants. Rattan commonly called Cane was identified in 1986 by Hutchinson as Calamusdeerratus. This species has two varieties one with large diameter which is referred to as big cane while the other is known as small Cane. The former ranges from 2 - 3cm in diameter, while the later ranges from 0.2 - 1.5cm in diameter (Okafor et al., 1994).

2.8.3 Nappier Grass (Pennisetum purpureum)

Nappier grass (Pennisetum purpurem), also known as elephant grass is indigenous to tropical Africa, and has been used for surface erosion control in many countries. The grass has good soil binding qualities and is easily propagated by planting of cuttings, which is advantageous on steep slopes and loosely consolidated soil.

The grass is an aggressive reproducer and spreads with short stout underground stems. It is multipurpose in that it is effective for surface erosion control and the leaves, young stems are good for fodder, exclusion of grazing animals is essential for initial growth and survival (Okafor et al., 1994).

2.9 Plant Uprooting

Two situations (or their combination) are likely to occur in natural situations during Plant's growth:

(a) When a simple upward force is exerted on the plant (e.g. by a grazing animal) and

(b) When a lateral force is exerted on the plant (usually by erosion).

In reality, the second of these situations is most likely to happen to woody and tall herbaceous plants, lateral forces on the plant would be more important than vertical forces and would result in uprooting. Uprooting is one of the most disastrous situations a plant might encounter during its life (Coutts 1983b, Ennos 1991). It is important to find out the influence of different factors to plant uprooting.

2.9.1 Plant Maximum Uprooting Force, F_{MAX}

Maximum Uprooting Force (F_{MAX}); is the force reached before uprooting a plant. Uprooting force could be lateral or vertical or a combination of both. The lateral uprooting force simulates to a certain extent plant failure during erosion or landslide.

2.9.2 Plant Uprooting Resistance, σ_{MAX}

The vast majority of self-supporting plants are likely to be uprooted by a herbivore, or even more likely by erosion. To neutralize lateral loads these plants are expected to have at least one rigid element (Ennos, 1993) that will resist with its bending resistance, while the surrounding soil resists with its compressive resistance.

Uprooting Resistance, σ_{MAX} is the critical stress (σ in mPa); ie the force per unit area necessary to induce uprooting. It is calculated as the maximum uprooting force, F_{MAX} divided by plant stem basal area A, (mm^2).

$$\sigma_{MAX} = F_{MAX}/A \quad (N/mm^2) \qquad (2.9)$$

But Area; $A = \pi D^2/4$ (2.10)

Where D = Plant stem basal diameter.

2.10 Statistical Analysis

Statistical techniques have long been central to the field of Science and Engineering. Statistics is usually considered as an essential element to data analysis and its application penetrates nearly all field of endeavor. The object of statistical methods is to collect relevant data, to arrange the data so that significant facts are established and perhaps rearrange same in order to permit comparisons with other statistical facts (Nwaogazie, 2006).

2.10.1 Regression Analysis

Regression analysis is a statistical process for estimating the relationships among variables; (Nwaogazie, 2006). Usually, the investigator seeks to ascertain the causal effect of one variable upon another; example, the effect of plant morphological traits on uprooting resistance. To explore such issues, the investigator assembles data on the underlying variables of interest and employs regression to estimate the quantitative effect of the causal variables upon the variables that they influence. The investigator also typically assesses the "statistical significance" of the estimated relationships, that is, the degree of confidence that the true relationship is close to the estimated relationship.

The simplest type of regression model is a linear model that is an equation of a straight line which can be represented by the equation:

$$Y = a_0 + a_1X \quad (2.11)$$

Where Y = dependent variable,

X = independent variable,

a_0 = Value of Y when X is equal to zero.

a_1 = multiplier that describes the size of the effect that X variable is having on Y.

For a quadratic model, that is parabola;

$$Y = a_0 + a_1X + a_2X^2 \quad (2.12)$$

For a cubic model;

$$Y = a_0 + a_1X + a_2X^2 + a_3X^3 \quad (2.13)$$

Analysis of a linear regression can be extended to cover situations in which the dependent variable is affected by several controlled variables (independent variables). For example, consider a case in which three controlled variables x_1, x_2 and x_3 are involved. A corresponding linear but multiple regression equation is of the form:

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_3 \quad (2.14)$$

Equation (2.13) is a linear multiple regression equation of y on x_1, x_2 and x_3. The dependent variable y varies partially due to variations in x_1, x_2 and x_3 respectively, the coefficients a_1, a_2 and a_3 represent partial regression coefficients of y on x_1 with, x_2 and x_3 held constant; y on x_2 with, x_1 and x_3 held constant; y on x_3 with, x_1 and x_2 held constant, respectively.

Consider a regression model of the form:

$$Y = CX^{a_1}z^{a_2} \quad (2.15)$$

Where x and z are the independent variables, C, a_1 and a_2 are constants. Equation (2.15) can be linearized or transformed to multiple regression models by taking logarithm of both sides. That is:

$$\mathrm{Log}Y = \mathrm{Log}C + a_1\mathrm{Log}X + a_2\mathrm{Log}z \quad (2.16)$$

Thus the estimate of coefficients C, a_1 and a_2 can be obtained by setting:

$Y_1 = \mathrm{Log}Y$; $a_o = \mathrm{Log}C$; $X_1 = \mathrm{Log}X$ and $X_2 = \mathrm{Log}z$.

$$.:Y_1 = a_0 + a_1X_1 + a_2X_2 \quad (2.17)$$

Apparently, Equation (2.15) has been transformed to take the form of Equation (2.14) and the solution procedure is same.

2.10.2 Correlation Coefficient

Correlation coefficient is a number between -1 and 1 that determines whether two paired sets of data (such as those for plant uprooting force and plant stem basal diameter) are related. The closer to 1 the more 'confident' we are of a positive linear correlation and the closer to –1 the more confident we are of a negative linear correlation (which happens when, for example one set of numbers tends to decrease when the other set increases. When the correlation coefficient is close to zero there is no evidence of any relationship. Confidence in a relationship is formally determined not just by the correlation coefficient but also by the number of pairs in your data. If there are very few pairs then the coefficient needs to be very close to 1 or –1 for it to be deemed 'statistically significant', but if there are many pairs then a coefficient closer to 0 can still be considered 'highly significant'.

2.10.3 Probability level

The standard method that statisticians use to measure the 'significance' of their empirical analyses is the ***p*-value**. Suppose we are trying to determine if the relationship between plant uprooting force and plants stem basal diameter is significant; then we start with the 'null hypothesis' which, in this case is the statement 'Uprooting force and basal diameter of plants are unrelated'. The *p*-value is a number between 0 and 1 representing the probability that this data would have arisen if the null hypothesis were true. A low *p*-value (such as 0.01) is taken as evidence that the null hypothesis can be rejected. Statisticians say that a *p*-value of 0.01 is 'highly significant' or say that 'the data is significant at the 0.01 level'. A competent researcher investigating a hypothesized relationship will set a *p*-value in advance of the empirical study. Typically, values of either 0.01 or 0.05 are used. If the data from the study results in a *p*-value of less than that specified in advance, the researcher will claim that their study is significant and it enables them to reject the null hypothesis and conclude that a relationship really exists.

2.10.4 Variance (S^2)

Variance, (S^2) is the mean squared deviation as measured by the second moment about the mean and is designated as:

$$S^2 = \sum_{i=1}^{N}(X_i - X)^2/N \qquad (2.18)$$

S^2 = Variance,

$\bar{X}$ = Arithmetic average,

N = Number of data points.

2.10.5 Statistical Hypotheses: Null and Alternative Hypotheses

Any assumption or guesses which may be true or false about the population made in order to reach a decision is taken as statistical hypotheses.

Null Hypotheses: statistical hypotheses are often times formulated first for the sake of nullifying or rejecting them. It is denoted by H_0.

Alternative Hypotheses: This will always differ from the null hypothesis and is denoted by H_1. In any test, the experimenter has to weigh the evidence and if possible decide between two hypotheses, H_0 and H_1. Essentially, the null hypotheses must be assumed to be true until the data indicates otherwise. Thus the burden of proof is on H_1 and the experimenter is interested in departures from H_0 rather than from H_1.

2.10.6 The studentised Range Test

The studentisd range may be defined as follows:

$$Sr = \text{Range}\ (\bar{X}_1, \bar{X}_2, \bar{X}_3, \ldots\ldots, \bar{X}_p)/S \qquad (2.19)$$

Where S_r = studentised range for a set of p treatment (each of which is the mean,

$\bar{X}_i = \Sigma X_i/n$)

X_i = random sample of n observations from a normal distribution and

S = Sample variance.

2.10.7 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a statistical method used to test differences between two or more means. In the ANOVA setting, the observed variance in a particular variable is partitioned into components attributable to different sources of variation. In its simplest form, ANOVA provides a statistical test of whether or not the means of several groups are equal. ANOVA are useful in comparing (testing) three or more means (group or variables) for statistical significance. The following steps are to be followed in carrying out ANOVA.

1. State the null and alternative hypotheses to help pass judgment as to whether there is or there is no significant difference between group means.

2. Classify observations into P mutually exclusive categories called one way classification, that is, variation within groups and variations between groups.

3. Obtain the independent estimates of the population variance, s^2 from the variation within groups.

4. Obtain the combined estimate of s^2 from the variations within group:

$$S_{WG}^2 = \sum_{i=1}^{P}\sum_{j=1}^{n}(X_{ij} - \bar{X}_i)^2/(P(n-1)) = \sum_{i=1}^{P} S_i^2/P \quad (2.20)$$

Where S_{WG}^2 = Variance within group (or residual variation).

5. Next, obtain estimate of variations between groups (taking into account the standard error of the means, $S/\sqrt{n}$) as:

$$S_{BG}^2 = \sum_{i=1}^{P}(\bar{X}_i - \bar{X})^2/(P-1) \quad (2.21)$$

Where S_{BG}^2 = Variance between groups.

6. Obtain total variation by adding the sum of squares between groups and within groups.

7. Compute the test statistic, F-value by dividing Equation (2.21) with Equation (2.20) as:

$$\text{F-value} = S_{BG}^2/ S_{WG}^2 \quad (2.22)$$

8. Obtain the upper percentage point F_{α,V_1,V_2} on the F- distribution with v_1 and v_2 degree of freedom at a given level of significance (1%, 5% etc).

9. Compare value of computed F-value with F_{α,V_1,V_2} for the purpose of passing judgment.

Table 2.2: Parameters for One-way Analysis of Variance (ANOVA).

Source of variation (1)	Sum of squares (2)	Degree of freedom (3)	Mean square (4)
Between groups	$\sum_{i=1}^{P}(X_i - X)^2$	P-1	S_{BG}^2 = Col 2/Col3
Within groups	$\sum_{i=1}^{P}\sum_{j=1}^{n}(X_{ij} - X_i)^2$	P(n-1)	S_{WG}^2 = Col2/Col3
Total Variation	$\sum_{i=1}^{P}\sum_{j=1}^{n}(X_{ij} - X_i)^2$	Pn - 1	

CHAPTER THREE

MATERIALS AND METHODS

3.1 MATERIALS

Twelve species from the local vegetation found within Nguzu – Edda Erosion site were chosen (Table 3.1). These species were selected according to certain criteria which include:

(i.) They are prevalent on the eroded land of Nguzu Edda and have different growth forms and families to obtain contrasted responses to uprooting and to measure a large range of plant trait values.

(ii.) They all have tap-like root systems, i.e. with an identifiable main vertical root and smaller lateral roots growing horizontally and vertically, to simplify the analysis and species comparison.

(iii.) Species already used by practitioners for land management were favoured.

(iv.) Species are available at the development stage investigated, i.e. juvenile individuals (stem basal diameter < 20 mm) in a relatively isolated position to avoid root system interaction between plants and modifications of anchorage strength.

(v.) species are available on flat areas since slope angle influences root system architecture and anchorage mechanics.

Five (5) trees (*Anacardium occidentale, Mangifera indica, Anacardium occidentale, Milicia excelsa and Citrus sinensis*), three (3) shrub species (*Oxytenanthera abyssinica*, *Vernonia amygdalina and Saccharum officinarum*) and four (4) herbaceous species (*Pennistum purpureum*, *Cynodon dactylon*, *Paspalum notatum* and *Chrysopogon zizanioides*). The species selected represented different families and successional status. Some species, such as *Elinaeis guiaensis*, despite their abundance in local vegetation, could not be included in the selection because they were not available at the juvenile stage at the site investigated. Uprooting tests and trait measurements were carried out between June and July in 2014 at the peak of vegetative growth. During the experiment, plants were selected to represent different stem basal diameters and thus to represent species anchorage strength and species morphology throughout the range of diameters studied (2–20 mm).

Table 3.1 Classification and sampling of plant species

Species	Family	Growth form	Number of Sampling site
Oxytenanthera abyssinica	Poaceae	S	1
Vernonia amygdalina	Asteraceae	S	1
Saccharum officinarum	Poaceae	S	1
Citrus sinensis	Rutaceae	T	1
Mangifera indica	Anacardiaceae	T	2
Anacardium occidentale	Anacardiaceae	T	1
Azadirachta indica	Meliaceae	T	1
Milicia excelsa	Moraceae	T	2
Pennistum purpureum	Poaceae	H	2
Cynodon dactylon	Poaceae	H	2
Paspalum notatum	Poaceae	H	1
Chrysopogon zizanioides	Poaceae	H	1

T = Tree; S = Shrub; H = Herbaceous

3.1.2 Study Site.

The experiment was conducted in the Nguzu – Edda erosion site. This area lies between latitude $5^0 50^1$ N and $6^0 00^1$ N and longitude $7^0 55^1$E and $7^0 57^1$ E within the Afikpo sycline of the Cross River basin of the Benue Trough. The area lies within the evergreen rain forest region but has been turned into secondary forest and derived savannah as a result of human activities. The annual total precipitation is 2083mm and the average annual temperature is 10.2°C. Vegetation has developed on partly eroded land and the slopes are covered with a loose regolith layer.

The dominant tree species on the site is Bambusa ssp; Forming massive reforestation operations for erosion control dating from the beginning of the last century . The other dominant plant species are Pennisetum Purpurem ,Calamusdeerratus and (*Saccharum officinarum*), Bahia grass (*Paspalum notatum*), Napier grass (*Pennisetum purpureum*), vetiver grass (*Vetiver zinzaniodes*), durva grass (*Cynodon dactylon*), *Vernonia amygdalina, Azadirachta indica.*

3.2 Data collection

Primary data from the case study were collected through lateral in-situ uprooting tests (using scale force gauge) and measurement of aboveground/underground traits of the uprooted plants.

3.2.1 Lateral in-situ uprooting test.

The instrument used for the lateral in-situ uprooting test is a scale force gauge; which measures the uprooting force and is primarily used for the estimation of the uprooting strength or resistance. Uprooting tests were performed on six (6) samples per specie. Before each test, the superficial litter layer was removed to clear the stem base; plant height and stem basal diameter were then measured. A non-stretch rope was bound to the stem base at one end and to a portable force gauge at the other end. A horizontal traction force was then applied manually until the plant was uprooted. Whenever the sample area was not completely flat, the force was applied parallel to the down slope direction. The main disadvantage of this method is that speed of pulling, which influences anchorage resistance, was not controlled. Consequently, the traction force was applied slowly, as regularly as possible, to avoid altering the results. Many uprooting tests failed because of rope or stem breakage or the rope slipping around the stem. During the valid tests, as the plants began to fail, roots could be heard breaking until complete root breakage and root system dislodgement from the sediment. The maximum force (F_{max}) reached before uprooting was noted and the critical stress (σ_{MAX}), i.e. the force per unit area necessary to induce uprooting, was calculated as F_{max} divided by plant stem basal cross-sectional area (mm^2). Plate 3.1 shows a lateral uprooting test being carried out on a young juvenile plant. To prevent soil moisture content differences, the tests were carried out in the morning, at least 2 days after an intensive rainfall event. Soil shear strength at 5cm and 10cm depths were measured to determine the soil's mechanical properties. Repeated measures of analysis of variance showed that soil cohesion increased with soil depth but that there were no significant differences in soil shear strength between locations.

Plate 3.1- Lateral uprooting test in Nguzu-Edda Erosion Site 1

3.2.2 Measurement of plants morphological traits

Morphological traits were measured based on existing literature of anchorage mechanics and root traits. Eight morphological traits were selected as presented in Table 3.2. For each species, six juvenile plants were tested. The week following harvest, the plants were cleaned using a fine stream of water to remove soil particles. After cleaning, plant height (H) and stem basal diameter (D) were measured. Root samples were separated into tap root (R_1) and lateral roots and were conserved until analysis. Various measuring tools were used to measure and estimate the morphological traits of the uprooted plants which include measuring tape, venier caliper, micrometer screw gauge, weighing scale. The traits parameters are represented as shown in Table 3.2.

Table 3.2: Morphological traits of specimen

Traits	Abbreviations (units)	Measurement
Plant slenderness ratio	H/D ($cm.cm^{-1}$)	H/D
Root slenderness ratio	LR1/D ($cm.cm^{-1}$)	LR1/D
Relative root volume	V/D ($cm3.cm^{-1}$)	V/D
Relative root dry weight	DWR/D ($g.cm^{-1}$)	DWR/D
Percentage of root system dry weight accounted for by the tap root	%DWR1 (%)	DWR1/DWR
Root Tissue Density	RTD ($g.cm^{-3}$)	DWR/V
Specific Root Length	SRL ($m.g^{-1}$)	L/DWR
Proportion of root length with diameter < 0.5 mm	%FR (%)	Fine root length (d< 0.5 mm)

3.3 Method of Data Analysis

An analysis of variance (ANOVA) was used to test for differences between species in uprooting resistance and traits. Duncan's multiple range tests were used to classify species into three resistance groups; a discriminant analysis was then performed to determine which traits best discriminate between the groups. Trait differences between groups were investigated with ANOVA. Multiple regression and correlation analysis were used to investigate relationships between resistance to uprooting and plant morphological traits.

CHAPTER FOUR

RESULTS AND ANALYSIS

4.1 RESULTS

The lateral in-situ uprooting tests and the measurement of above ground and underground traits of young plants were carried out as already outlined. The results are presented in Table 4.1 to Table 4.74.

4.1.1 Results of Soil Test.

The results of the soil tests carried out are shown in Table 4.1.

Table 4.1: Soil Shear Strength (k Pa) at 5cm and 10cm depths at sites 1 and 2

Depth	Characteristics	Site 1	Site 2
5 cm	Mean	65.5	58.2
	SE	3.15	3.15
10 cm	Mean	125.5	150.5
	SE	8.9	9.5

SE = standard error.

From Table 4.1, the soil cohesion increased with soil depth but there were no significant difference in the soil shear strength between locations. Therefore there is strong indication of homogeneous nature of soil between the two sites.

4.1.2 Uprooting Test and Above Ground Traits

Table 4.2 shows Above-ground traits measured values and maximum uprooting force (F_{MAX}) for all the species studied. The above ground traits measured are plant height (H), stem basal diameter (D).

Table 4.2: Above ground traits and Uprooting force of plant species studied

Species	Plant height, H (cm)			Stem basal diameter (mm)			Uprooting force, $F_{Max.}$ (N)			Number of valid tests.
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	
O. abyssinica	68.0	53.0	91.0	14.6	10.0	19.2	549.0	210.0	847.0	6
C. sinensis	48.9	31.2	66.1	14.1	12.7	15.9	400.2	193.8	735.0	6
V. amygdalina	56.02	42.0	82.1	15.9	12.5	17.9	637.3	480.0	830.0	6
P.purpureum	34.08	25.0	57.0	6.67	6.0	7.2	40.27	28.3	68.8	6
C. dactylon	27.68	17.4	47	3.84	2.0	6.5	17.45	5.5	28.7	6
S.officinarum	61.08	45.0	83.0	12.83	10.0	16.9	161.82	95.0	246.0	6
M.indica	54.5	36.3	87.5	15.38	10.5	18.6	418.0	255.0	837.0	6
A.occidentale	45.25	32.0	75.0	13.37	11.0	18.0	342.5	195.0	855.0	6
A. indica	48.5	26.5	68.5	16.8	12.0	19.5	432.0	195.0	741.0	6
M. excelsa	60.5	45.0	85.0	15.0	10.5	18.5	555.0	246.0	780.0	6
P. notatum	23.98	19.0	34.0	7.57	4.5	12.4	47.88	22.5	92.5	6
C. zizaniodes	25.5	15.0	30.0	7.37	4.2	13.5	18.9	10.0	35.0	6

In all species, the maximum uprooting force increased with stem basal diameter, a surrogate for plant size: the larger the plant, the higher its anchorage strength. The graphical presentations of the results in Table 4.2 are illustrated in Figure 4.1, Figure 4.2 and Figure 4.3.

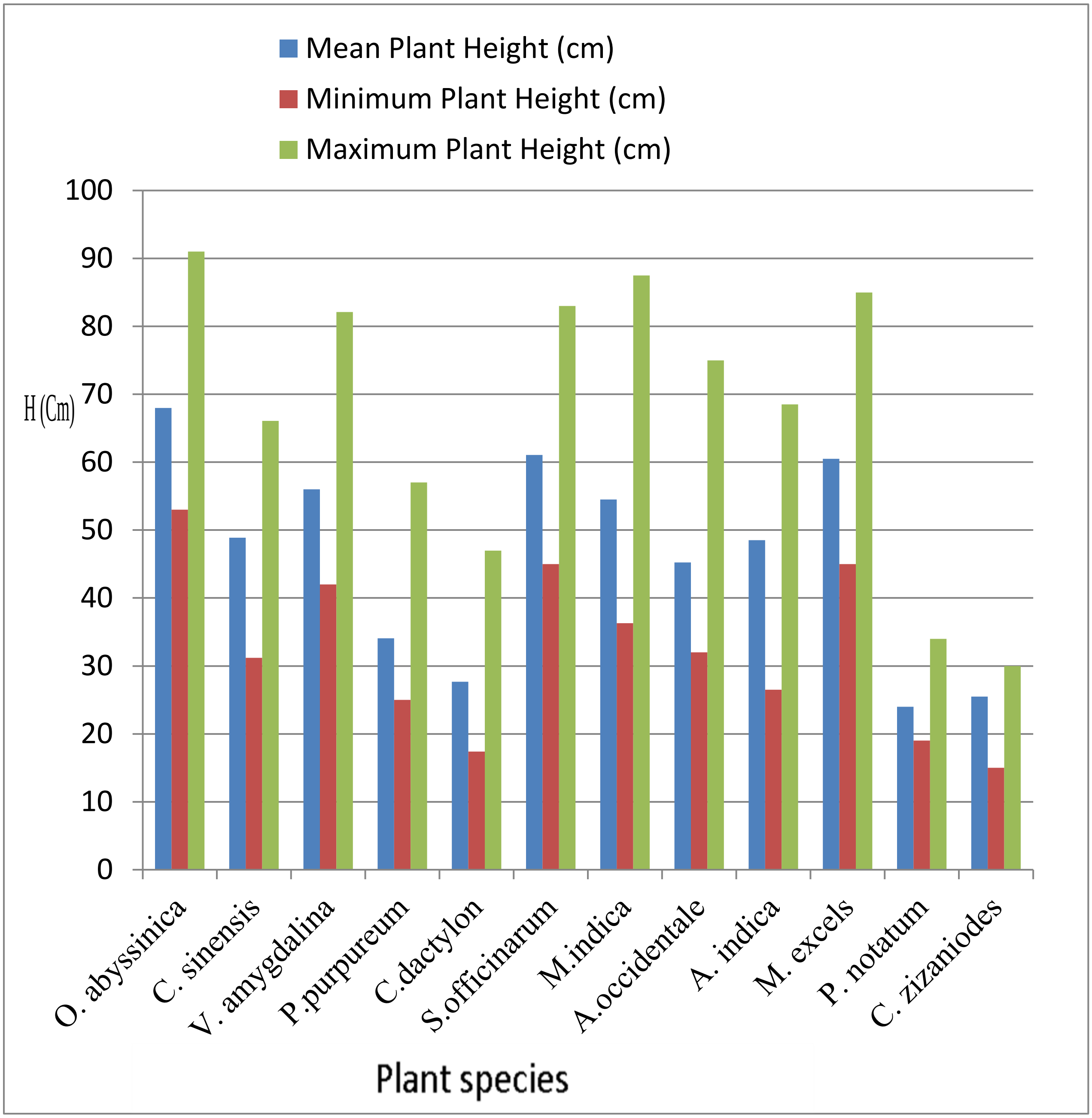

Figure 4.1: Plants height for the twelve species.

Plant height (H) showed large inter and intra specific variability. For example, the plant height (H) of O. abyssinica ranged from 53cm to 91cm while for C. zizaniodes the range is from 15.0cm to30.0cm.

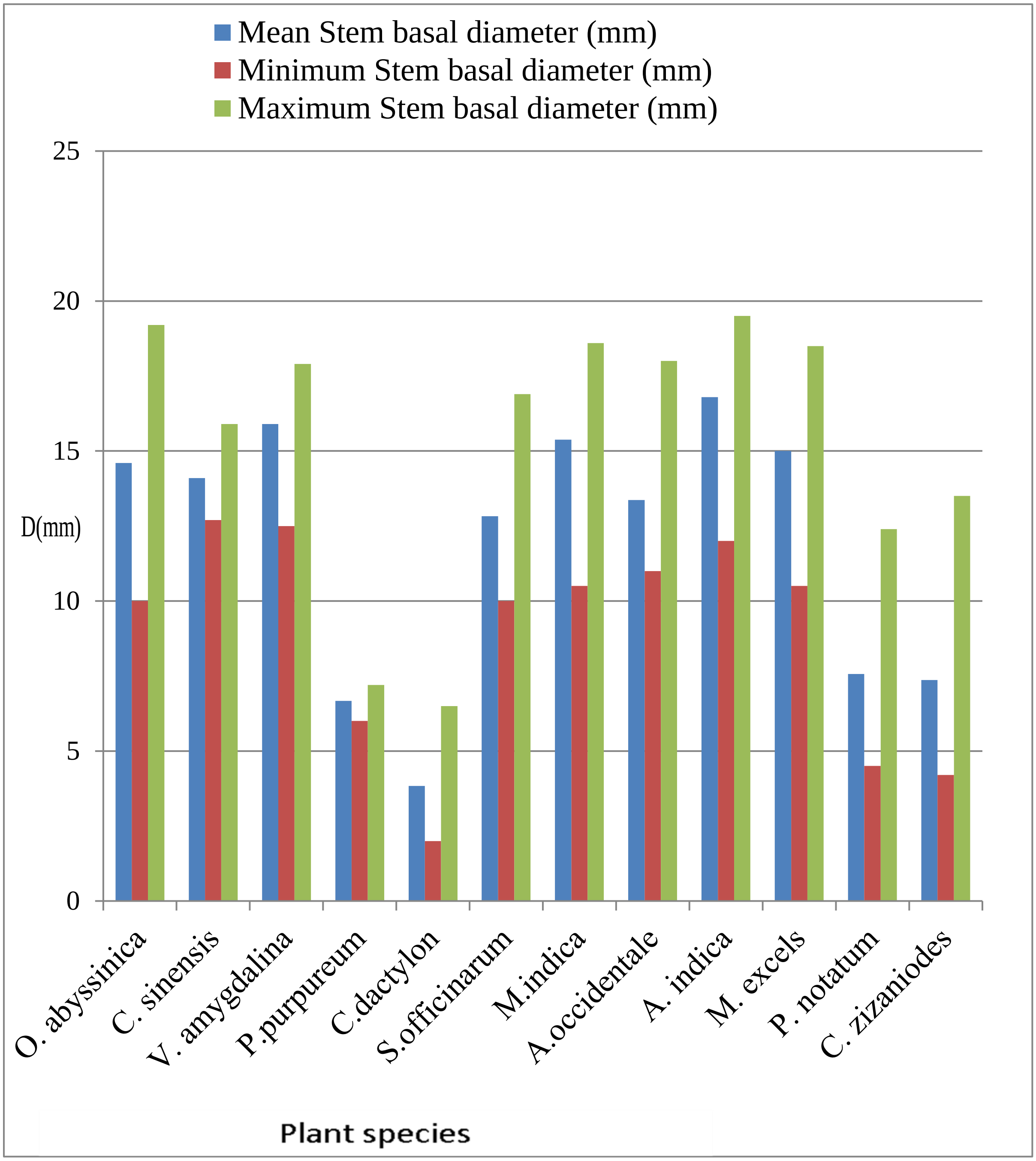

Figure 4.2: Plant stem basal diameter for the twelve species

Plant stem basal diameter (D) showed large inter and intra specific variability. It ranges from 2mm (C. dactylon) to 19.5mm (A. indica).

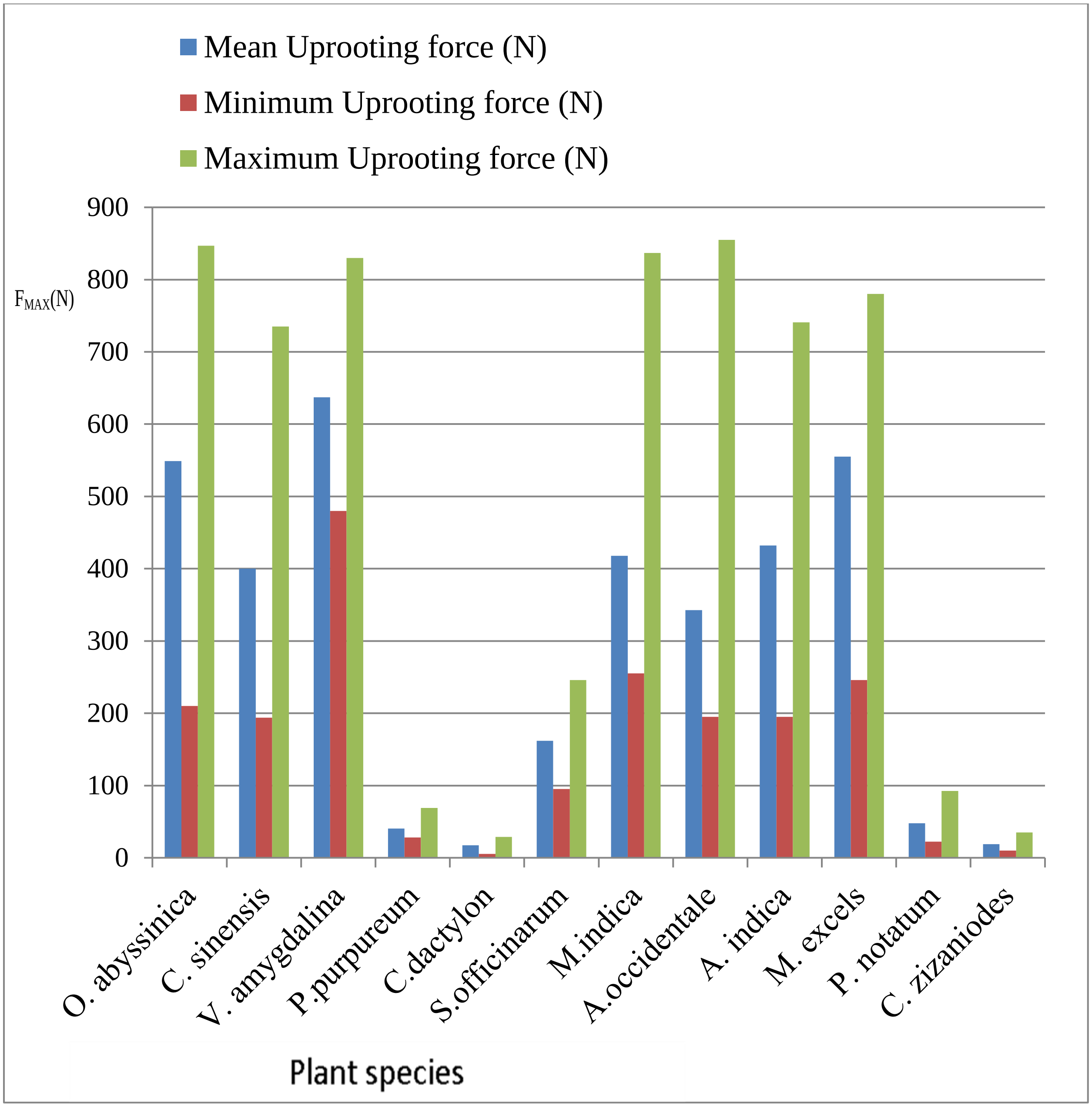

Figure 4.3: Uprooting force for the twelve species.

Uprooting force (F_{MAX}) showed large inter-and intra-specific variability. It recorded least value of 5.5N (C. zizaniodes) and the highest value of 855N (*A. occidentale*). This large variability in F_{max} is mainly explained by the variation in D.

4.2.1 REGRESSION ANALYSIS OF MAXIMUM UPROOTING FORCE (F_{Max}) ON PLANT STEM BASAL DIAMETER (D)

Regression analysis of maximum uprooting force (F_{Max}) on plant stem basal diameter (D) investigates the relationship between the plant stem basal diameter and the maximum uprooting force.

4.2.1.1 Regression Analysis of *O. abyssinica*`s Maximum Uprooting Force (F_{Max}) on Stem Basal Diameter (D)

For the regression analysis of *O. abyssinica*`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), the details of uprooting tests and above ground traits of O. abyssinica is shown in Table 4.3.

Table 4.3: Above-ground Traits/Maximum Uprooting Forces of *Oxytenanthera abyssinica* (Bamboo)

Test No	1	2	3	4	5	6	Mean
Plant Height H (cm)	85.0	49.5	91.0	76.5	53.0	53.0	68.0
Stem Basal Diameter, D(mm)	18.0	15.5	19.2	14.5	10.4	10.0	14.6
Maximum Uprooting Force; F_{MAX}(N)	790.0	210.0	847.0	669.0	390.0	387.0	549.0

For the linear regression analysis of *O. abyssinica*`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), the linear regression model is found to be of the form:

$$F_{MAX} = a_0 + a_1 D \qquad (4.1)$$

F_{MAX} = Maximum Uprooting force

a_0 = Value of F_{MAX} assuming D is negligible.

a_1 = multiplier that describes the size of the effect that D is having on F_{MAX}.

D = Plant stem basal diameter

The applicable normal equations for obtaining estimates of a_0 and a_1 are as follows:

$\Sigma F_{MAX} = a_0 n + a_1 \Sigma D$ (4.2a)

$\Sigma F_{MAX*}D = a_0 \Sigma D + a_1 \Sigma D^2$ (4.2b)

The terms of Equation (4.2a) and Equation (4.2b) are evaluated as shown in Table 4.4

Table 4.4: Evaluated Terms for *O. abyssinica*`s Linear Regression model of F_{max} and D.

TEST NO	F_{MAX}(N)	D(mm)	F_{MAX*}D	D^2 (mm^2)
1	790	18	14220	324
2	210	15.5	3255	240.3
3	847	19.2	16262	368.6
4	669	14.5	9701	210.3
5	390	10.4	4056	108.2
6	387	10	3870	100
Σ	3293	87.6	51364	1351

The resulting normal equations with direct substitution of terms in Table 4.4 into Equation (4.2a) and Equation (4.2b) are:

$3293 = 6a_0 + 87.6a_1$ (4.3a)

$51364 = 87.6a_0 + 1351a_1$ (4.3b)

Solving Equations (4.3a) and (4.3b), and substituting for a_0 and a_1 into Equation (4.1) we obtain:

$F_{MAX} = -117.22 + 46D$ (4.4)

The Coefficient of Determination, $r^2 = 0.999$; while p = 0.00000037.

Equation 4.4 is the linear regression model of F_{MAX} on D for *O. abyssinica* while the graphical illustration of the linear relationship is shown in Figure 4.4.

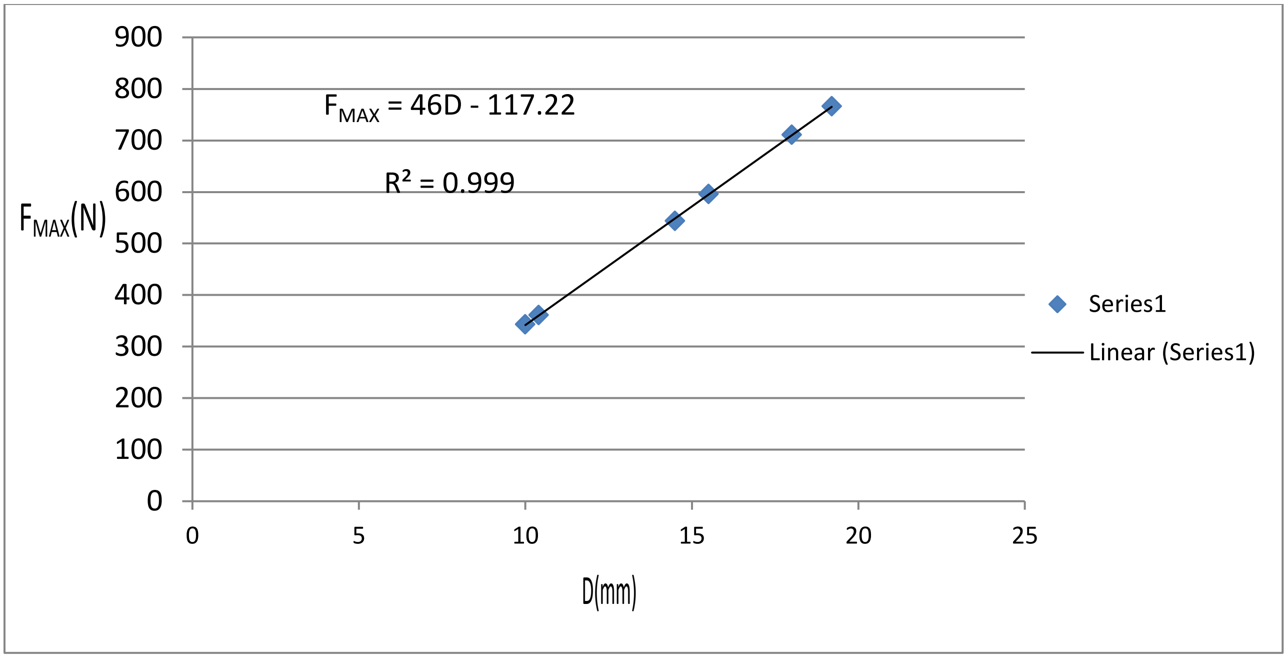

Figure 4.4: Linear regression of F_{MAX} on D for *O. a*byssinica species

Assuming Quadratic regression model of the form;

$$F_{MAX} = a_0 + a_1D + a_2D^2 \qquad (4.5)$$

Where; F_{MAX} = Maximum Uprooting force

a_0 = Value of F_{MAX} assuming

a_1, a_2 are regression coefficients.

D = Plant stem basal diameter

The applicable normal equations for obtaining estimates of a_0, a_1 and a_2 are as follows:

$$\Sigma F_{MAX} = a_0n + a_1\Sigma D + a_2\Sigma D^2 \qquad (4.6a)$$

$$\Sigma F_{MAX*}D = a_0\Sigma D + a_1\Sigma D^2 + a_2\Sigma D^3 \qquad (4.6b)$$

$$\Sigma F_{MAX*}D^2 = a_0\Sigma D^2 + a_1\Sigma D^3 + a_2\Sigma D^4 \qquad (4.6c)$$

The terms of Equation (4.6a), Equation (4.6b) and Equation (4.6c) are evaluated as shown in Table 4.5

Table 4.5: Evaluated Terms for *O. abyssinica`s* Quadratic Regression of Maximum Uprooting Force (F_{MAX}) on Stem Basal Diameter (D).

Test no	1	2	3	4	5	6	Summation
F_{MAX} (N)	790	210	847	669	390	387	3293
D(mm)	18.0	15.5	19.2	14.5	10.4	10.0	87.6
$F_{MAX}*D$	14220	3255	16262	9701	4056	3870	51364
D^2	324	240.3	368.6	210.3	108.2	100	1351
$F_{MAX}*D^2$	255960	50463	50463	140690.7	42198	38700	840215.9
D^3	5832	3723.875	7077.89	3048.625	1124.864	1000	21807.252
D^4	104976	57720.0625	135895.4496	44205.0625	11698.5856	10000	364495.1602

The resulting normal equations with direct substitution of terms in Table 4.5 into Equation (4.6a), Equation (4.6b) and Equation (4.6c) are:

$$3293 = 6a_0 + 87.6a_1 + 1351a_2 \quad (4.7a)$$

$$51364 = 87.6a_0 + 1351a_1 + 21807.252a_2 \quad (4.7b)$$

$$840215.9 = 1351a_0 + 21807.252a_1 + 364495.1602a_2 \quad (4.7c)$$

Solving for the unknown coefficients of Equation (4.7a), Equation (4.7b) and Equation (4.7c), (see matrix A.1 and matrix A.2 in appendix A), we have:

$a_2 = 43.0679$, $a_1 = -1199.4213$, $a_0 = 8362.9274$.

Thus the least square quadratic equation is:

$$F_{MAX} = 8362.9274 - 1199.4213D + 43.0679D^2 \quad (4.8)$$

The Coefficient of Determination, $r^2 = 0.88$; while $p = 0.00474$.

Equation 4.8 is the quadratic regression model of F_{MAX} on D for *O.abyssinica* while the graphical illustration of quadratic relationship is shown in Figure 4.5

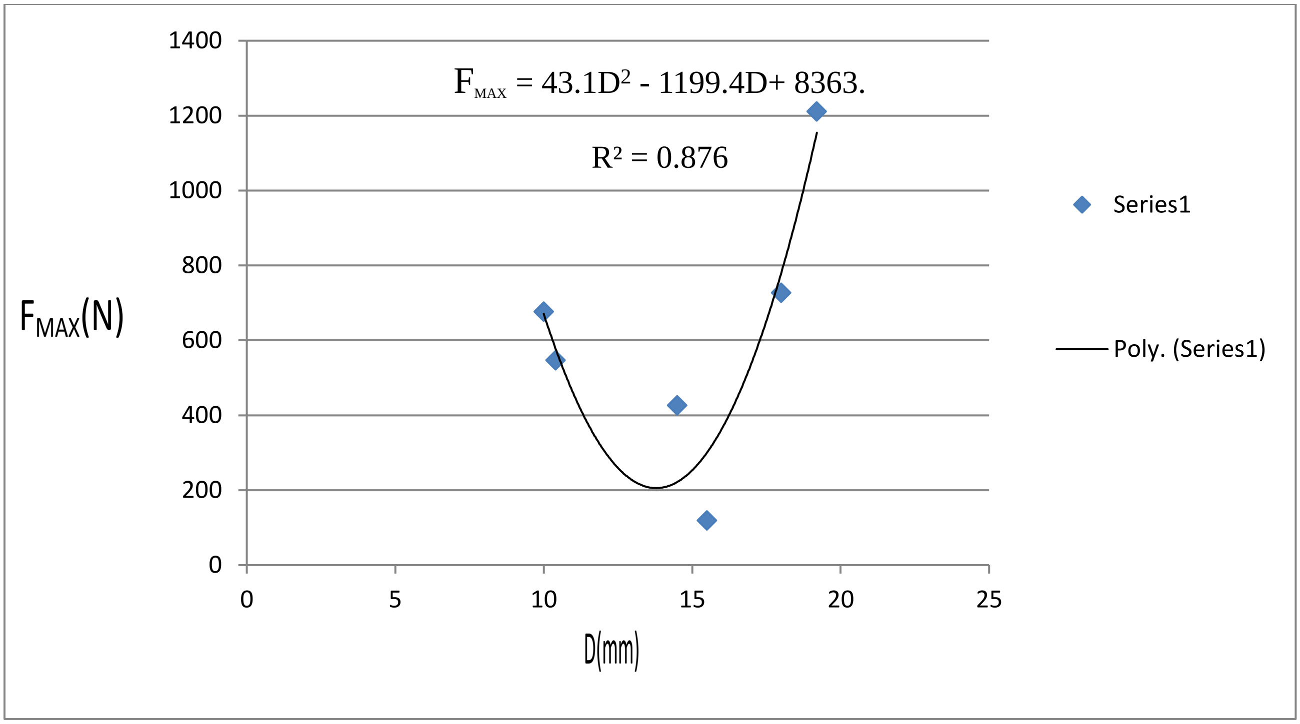

Figure 4.5: Quadratic regression of F_{MAX} on D for *O. abyssinica* species

Going further to assume a cubic polynomial regression model of the form:

$$F_{MAX} = a_0 + a_1D + a_2D^2 + a_3D^3 \quad (4.9)$$

F_{MAX} = Maximum Uprooting force

a_0 = Value of F_{MAX} assuming D is negligible

a_1, a_2, a_3 are regression coefficients.

D = Plant stem basal diameter

The applicable normal equations for obtaining estimates of a_0, a_1, a_2 and a_3 are as follows:

$$\Sigma F_{MAX} = a_0n + a_1\Sigma D + a_2\Sigma D^2 + a_3\Sigma D^3 \quad (4.10a)$$

$$\Sigma F_{MAX}*D = a_0\Sigma D + a_1\Sigma D^2 + a_2\Sigma D^3 + a_3\Sigma D^4 \quad (4.10b)$$

$$\Sigma F_{MAX}*D^2 = a_0\Sigma D^2 + a_1\Sigma D^3 + a_2\Sigma D^4 + a_3\Sigma D^5 \quad (4.10c)$$

$\Sigma F_{MAX*}D^3 = a_0\Sigma D^3 + a_1\Sigma D^4 + a_2\Sigma D^5 + a_2\Sigma D^6$ (4.10d)

The terms of Equation (4.10a), Equation (4.10b), Equation (4.10c) and Equation (4.10d) are evaluated as shown in Table 4.6.

Table 4.6: Evaluated Terms for Cubic Polynomial Regression Model of Maximum Uprooting Force (F_{MAX}) on Stem Basal Diameter(D) for *O. abyssinica*

Test no	1	2	3	4	5	6	Σ
F_{MAX} (N)	790	210	847	669	390	387	3293
D(mm)	18.0	15.5	19.2	14.5	10.4	10.0	87.6
$F_{MAX*}D$	14220	3255	16262	9701	4056	3870	51364
D^2	324	240.3	368.6	210.3	108.2	100	1351
$F_{MAX*}D^2$	255960	50463	50463	140690.7	42198	38700	840215.9
D^3	5832	3723.875	7077.89	3048.625	1124.864	1000	21807.252
$F_{MAX*}D^3$	4607280	782013.75	5994971.136	2039530.125	438696.96	387000	14249491.97
D^4	104976	57720.0625	135895.4496	44205.0625	11698.5856	10000	364495.1602
D^5	1889568	894660.9688	2609192.632	640973.4063	121665.2902	100000	6256060.297
D^6	34012224	13867245.02	50096498.54	9294114.391	1265319.018	1000000	109535401

The resulting equations with direct substitution of terms in Table 4.6 into Equation (4.10a), Equation (4.10b), Equation (4.10c) and Equation (4.10d) are:

$3293 = 6a_0 + 87.6a_1 + 1351a_2 + 21807.252a_3$ (4.11a)

$51364 = 87.6a_0 + 1351a_1 + 21807.252a_2 + 364495.1602a_3$ (4.11b)

$840215.9 = 1351a_0 + 21807.252a_1 + 364495.1602a_2 + 6256060.297a_3$ (4.11c)

$840215.9 = 21807.252a_0 + 364495.1602a_1 + 6256060.297a_2 + 109535401a_3$ (4.11d)

Solving for the unknown coefficients (see matrix A.3 and matrix A.4 in Appendix A), we have:

$a_3 = 0.3328$, $a_2 = -5.9863$, $a_1 = 5.6686$, $a_0 = 604.4116$.

Thus the least square polynomial equation of third order is:

$$F_{MAX} = 604.4116 + 5.6686D - 5.9863D^2 + 0.3328D^3 \quad (4.12)$$

The Coefficient of Determination, $r^2 = 0.713$; $p = 0.0202$.

Equation 4.12 is the cubic regression model of F_{MAX} on D for *O. abyssinica* while the graphical illustration of cubic relationship is shown in Figure 4.6

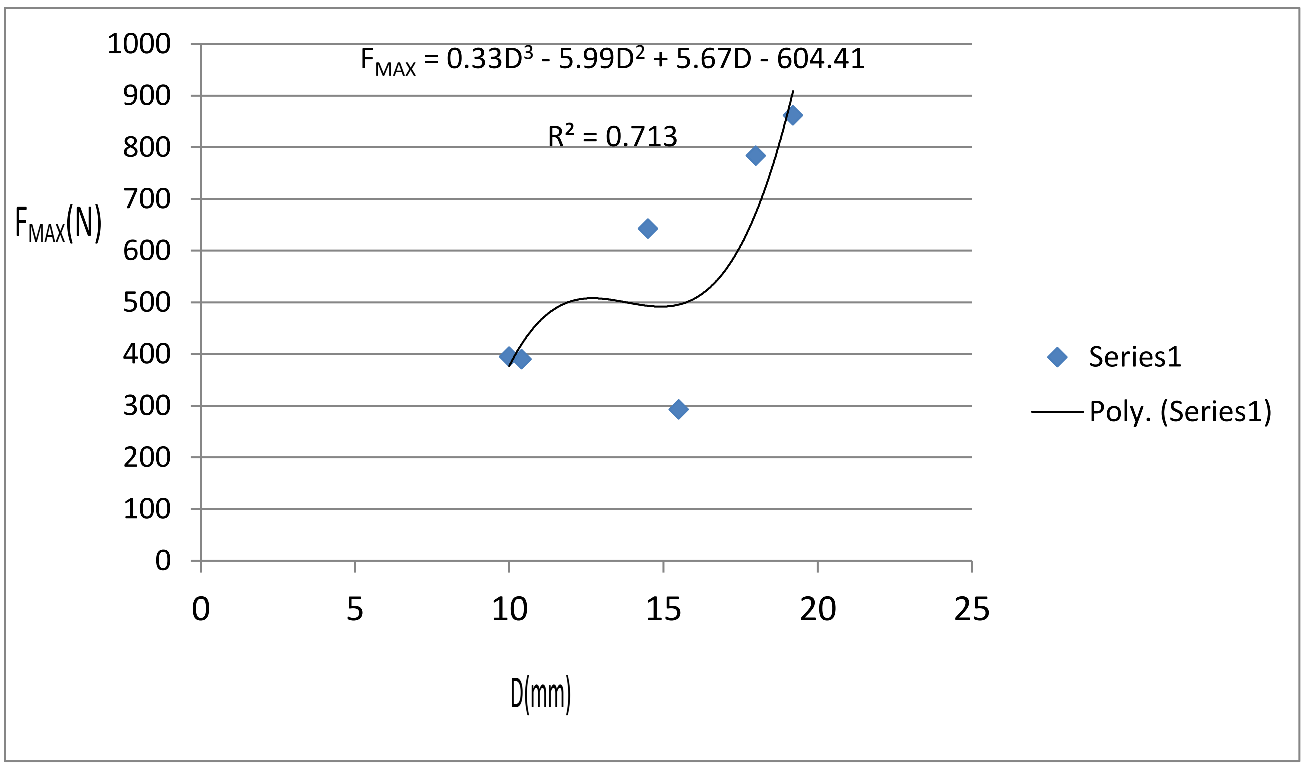

Figure 4.6: Cubic regression of F_{MAX} on D for *O. abyssinica* species

The summary of the three models for *O. abyssinica* species is presented in Table 4.7.

Table 4.7: Results of Regression Analysis of F_{MAX} on D for *O. abyssinica* species

Model	Equation	Coefficient of Determination(r^2)	Probability level (p)
Linear model	$F_{MAX} = 46D – 117.22$	0.999	0.00000037
Quadratic model	$F_{MAX} = 8362.9274-1199.4213D +43.0679D^2$	0.876	0.00474
Cubic polynomial model	$F_{MAX} = 604.4116+5.6686D – 5.9863D^2+0.3328D^3$	0.713	0.0202

The strength of a relationship is indicated by the Coefficient of Determination (r^2) and the significance, expressed by the probability level, p. Comparing the three models of Table 4.7, there is high linear positive relationship between Uprooting force, F_{MAX} and basal diameter (D); for *O. abyssinica* species.

4.2.1.2 Regression Analysis of *C. sinensis*`s Maximum Uprooting Force (F_{Max}) on Stem Basal Diameter (D)

For the regression analysis of *C. sinensis*`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), the details of uprooting tests and above ground traits of *C. sinensis* is shown in Table 4.8.

Table 4.8: Above Ground Traits/ Maximum Uprooting Forces of *Citrus Sinensis* (Juvenile Orange tree)

Test No	1	2	3	4	5	6	Mean
Plant Height H(cm)	66.1	55.0	65.0	31.2	35.7	40.5	48.9
Stem Basal Diameter D(mm)	15.9	13.5	14.2	12.7	13.6	14.5	14.07
Maximum Uprooting Force F_{MAX}(N)	735	480	570	193.8	197.4	225	400.2

For the linear regression analysis of *C. sinensis*`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), Equation (4.1), Equation (4.2a) and Equation (4.2b) are applied to the data in Table 4.8.

The evaluated parameters of these equations are presented in Table 4.9.

Table 4.9: Evaluated Terms for Linear Regression of F_{MAX} on D for *C.sinensis*

Test no	F_{MAX}(N)	D(mm)	$F_{MAX}*D$	D^2 (mm^2)
1	735	15.9	11687	252.8
2	480	13.5	6480	182.3
3	570	14.2	8094	201.6
4	193.8	12.7	2461	161.3
5	197.4	13.6	2685	185
6	225	14.5	3263	210.3
Σ	2401	84.4	34669	1193

The resulting normal equations with direct substitution of terms in Table 4.9 into Equation (4.2a) and Equation (4.2b) are:

$$2401 = 6a_0 + 84.4a_1 \quad (4.13a)$$

$$34669 = 84.4a_0 + 1193a_1 \quad (4.13b)$$

Solving Equations (4.13a) and (4.13b), and substituting for a_0 and a_1 into Equation (4.1) we obtain:

$$F_{MAX} = -1790.94 + 156D \quad (4.14)$$

The Coefficient of Determination, $r^2 = 0.999$; and $p = 0.00000037$.

Equation 4.14 is the linear regression model of F_{MAX} on D for *C. sinensis* while the graphical illustration of the linear relationship is shown in Figure 4.7

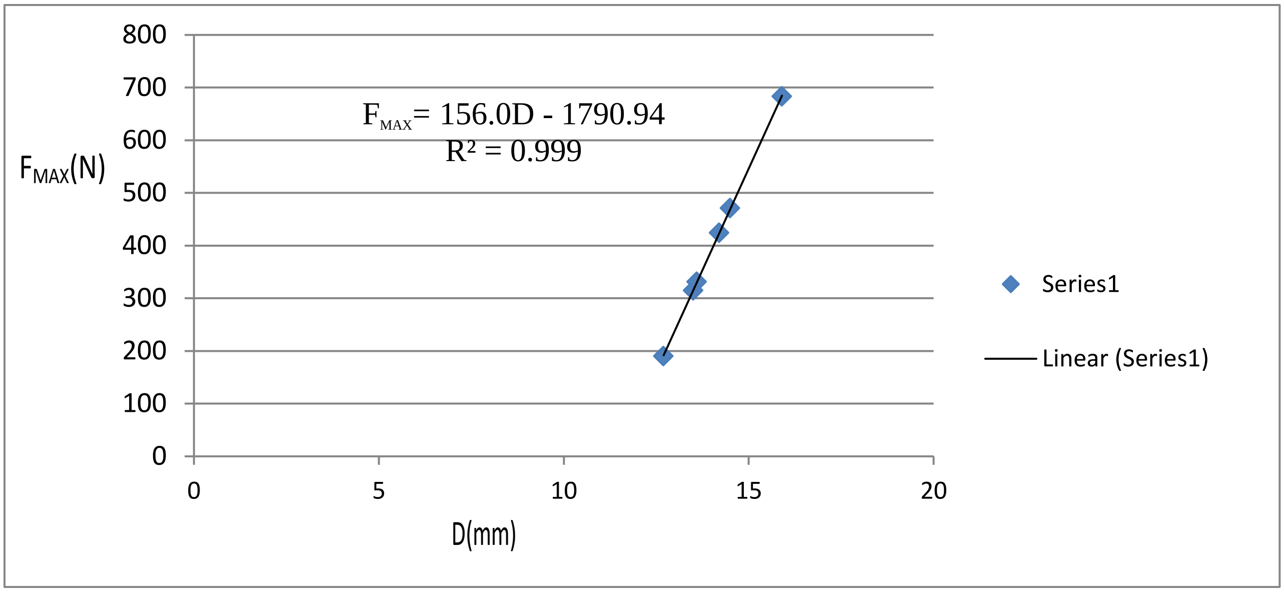

Figure 4.7: Linear regression of F_{MAX} on D for *C. sinensis* species

Assuming Quadratic regression model of the form as presented by Equation (4.5); Equation (4.6a), Equation (4.6b) and Equation (4.6c) are applied to the data in Table 4.8. The terms of these equations for *C. sinensis* species are evaluated in Table 4.10.

Table 4.10: Evaluated Terms for Quadratic Regression of F_{MAX} on D for *C.sinensis*

Test no	F_{MAX}	D	$F_{MAX}*D$	D^2	$F_{MAX}*D^2$	D^3	D^4
1	735	15.9	11687	252.8	185808	4019.679	63912.8961
2	480	13.5	6480	182.3	87504	2460.375	33215.0625
3	570	14.2	8094	201.6	114912	2863.288	40658.6896
4	93.8	12.7	2461	161.3	31259.94	2048.383	26014.4641
5	197.4	13.6	2685	185	36519	2515.456	34210.2016
6	225	14.5	3263	210.3	47317.5	3048.625	44205.0625
Σ	2401	84.4	34669	1193	503320.44	16955.80	24226.3764

The resulting normal equations with direct substitution of terms in Table 4.10 into Equation (4.6a), Equation (4.6b) and Equation (4.6c) are:

$$2401 = 6a_0 + 84.4a_1 + 1193a_2 \quad (4.15a)$$

$$34669 = 84.4a_0 + 1193a_1 + 16955.80a_2 \quad (4.15b)$$

$503320.44 = 1193a_0 + 16955.80a_1 + 24226.3764a_2$ (4.15c)

Solving for the unknown coefficients of Equation (4.15a), Equation (4.15b) and Equation (4.15c); (see matrix A.5 and matrix A.6 in Appendix A), we have:

$a_2 = 4.3224$, $a_1 = 24.5396$, $a_0 = -804.4615$.

Thus the least square quadratic equation is gotten by substituting the values of a_0, a_1 and a_2 into Equation (4.5). Thus:

$$F_{MAX} = -804.4615 + 24.5396D + 4.3224D^2 \quad (4.16)$$

The Coefficient of Determination, $r^2 = 0.986$; while $p = 0.0000718$.

Equation 4.16 is the quadratic regression model of F_{MAX} on D for *C. sinensis* while the graphical illustration of the quadratic relationship is shown in Figure 4.8.

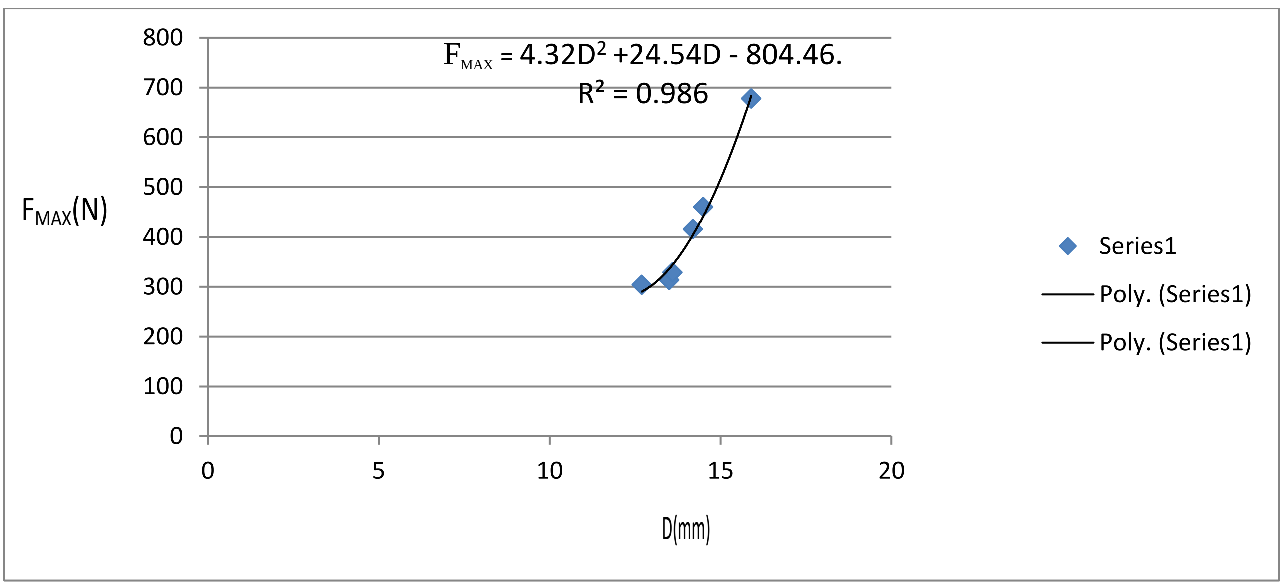

Figure 4.8: Quadratic regression of F_{MAX} on D for *C. sinensis* species

Going further to assume a cubic polynomial regression model of the form of Equation (4.9)

The applicable normal equations for obtaining estimates of the coefficients a_0, a_1,a_2 and a_3 are Equations (4.10a), (4.10b), (4.10c) and (4.10d).

The terms of Equation (4.10a), Equation (4.10b), Equation (4.10c) and Equation (4.10d) for *C. sinensis* are evaluated as shown in Table 4.11.

Table 4.11: Evaluated Terms for *C. sinensis*`s Cubic Polynomial Regression of Maximum Uprooting Force (F_{MAX}) on Stem Basal Diameter (D).

Test no	1	2	3	4	5	6	Σ
F_{MAX} (N)	790	480	570	193.2	197.4	225	2410
D(mm)	15.9	13.5	14.2	12.7	13.6	14.5	84.4
$F_{MAX}*D$	11687	6480	8094	2461	2685	3263	34669
D^2	252.8	182.3	201.6	161.3	185	210.3	1193
$F_{MAX}*D^2$	185808	87504	114912	31259.94	36519	47317.5	503320
D^3	4019679	2460.38	2863.288	2048.383	2515.5	3048.63	16955.8
$F_{MAX}*D^3$	2954464.065	1180980	1632074.16	396976.6254	496551.0144	685940.625	7346986.49
D^4	63912.8961	33215.0625	40658.6896	26014.4641	34210.2016	44205.0625	242216.3764
D^5	1016215.048	448403.3438	577353.3923	330383.6941	465258.7418	640973.4063	3478587.626
D^6	16157819.26	6053445.141	8198418.171	4195872.915	3275186.888	9294114.391	50227188.77

The resulting equations with direct substitution of terms in Table 4.11 into Equation (4.10a), Equation (4.10b), Equation (4.10c) and Equation (4.10d) are:

$$2410 = 6a_0 + 84.4a_1 + 1193a_2 + 16955.80a_3 \quad (4.17a)$$

$$34669 = 84.4a_0 + 1193a_1 + 16955.80a_2 + 242216.3764a_3 \quad (4.17b)$$

$$503320.44 = 1193a_0 + 16955.80a_1 + 242216.3764a_2 + 3478587.626a_3 \quad (4.17c)$$

$$7346986.49 =16955.8a_0 +242216.376a_1 +3478587.626a_2 +50227188.77a_3 \quad (4.17d)$$

Solving for the unknown coefficients of Equations (4.17a) to Equation (4.17d), (see matrix A.7 and matrix A.8 in Appendix A), we have:

$a_3 = 1.4461$, $a_2 = -30.2645$, $a_1 = 118.6566$, $a_0 = 663.5199$.

Thus the least square cubic polynomial is:

$$F_{MAX} = 663.5199+118.6566D -30.2645D^2+1.4461D^3 \quad (4.18)$$

The Coefficient of Determination, $r^2 = 0.65$; and $p = 0.02814$).

Equation 4.18 is the cubic regression model of F_{MAX} on D for *C. sinensis* while the graphical illustration of the cubic relationship is shown in Figure 4.9.

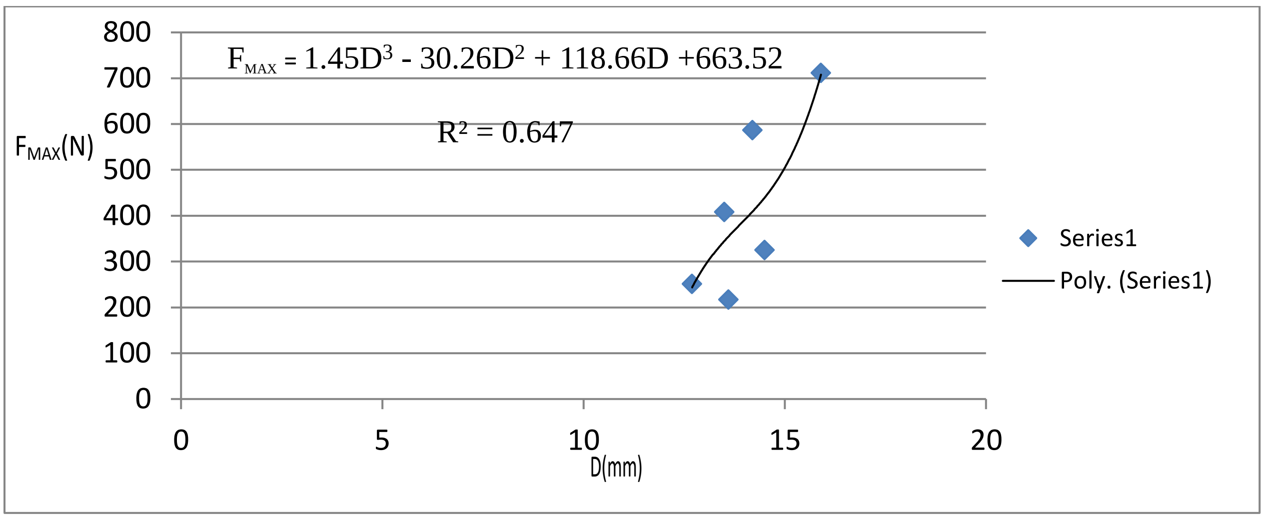

Figure 4.9: Cubic regression of F_{MAX} on D for *C. sinensis* species

The summary of the three models for *C. sinensis* species is presented in Table 4.12.

Table 4.12: Results of Regression Analysis of F_{MAX} on D for *C. sinensis* species

Model	Equation	Coefficient of Determination (r^2)	Probability level (p)
Linear model	$F_{MAX} = 156D – 1790.94$	0.999	0.00000037
Quadratic model	$F_{MAX} = -804.4615+24.5396D +4.3224D^2$	0.986	0.0000718
Cubic polynomial model	$F_{MAX} = 663.5199+118.6566D – 30.2645D^2+1.4461D^3$	0.647	0.02814

The strength of a relationship is indicated by the Coefficient of Determination (r^2) and the significance, expressed by the probability level, p. Comparing the three models of Table 4.12, the linear model has the best relationship between Uprooting force, F_{MAX} and basal diameter (D); for *C. sinensis* species.

4.2.1.3 Regression Analysis of *V. amygdalina*`s Maximum Uprooting Force (F_{Max}) on Stem Basal Diameter (D)

For the regression analysis of *V. amygdalina*`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), the details of uprooting tests and above ground traits of *V. amygdalina* is shown in Table 4.13.

Table 4.13: Above Ground Traits/Maximum Uprooting Force of *Vernonia amygdalina (*Bitterleaf)

Test No	1	2	3	4	5	6	Mean
Plant Height H(cm)	55.0	50.0	42.0	55.0	82.1	52.0	56.02
Stem Basal Diameter D(mm)	16.2	17.1	12.5	14.6	17.9	17.0	15.9
Maximum Uprooting Force F_{MAX}(N)	630	610	480	640	830	634	637.33

For the linear regression analysis of *V. amygdalina*`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), the linear regression model is found to be of the form of Equation (4.1) and the applicable normal equations for obtaining estimates of a_0 and a_1 are Equation (4.2a) and Equation (4.2b).

The terms of Equation (4.2a) and Equation (4.2b) for *V. amygdalina* are evaluated as shown in Table 4.14.

Table 4.14: Evaluated Terms for Linear Regression of Maximum Uprooting Force on Stem Basal Diameter for *V. amygdalina*

Test no	F_{MAX}(N)	D(mm)	$F_{MAX}*D$	D^2 (mm^2)
1	630	16.2	10206	262.4
2	610	17.1	10431	292.4
3	480	12.5	6000	156.3
4	640	14.6	9344	213.2
5	830	17.9	14857	320.4
6	634	17	10778	289
Σ	3824	95.3	61616	1534

The resulting normal equations with direct substitution of terms in Table 4.14 into Equation (4.2a) and Equation (4.2b) are:

$$3824 = 6a_0 + 95.3a_1 \quad (4.19a)$$

$$61616 = 95.3a_0 + 1534a_1 \quad (4.19b)$$

Solving Equations (4.19a) and (4.19b), and substituting for a_0 and a_1 into Equation (4.1) we obtain:

$$F_{MAX} = -48.067 + 43.2D \quad (4.20)$$

The Coefficient of Determination, $r^2 = 0.999$; and $p = 0.00000037$.

Equation 4.20 is the linear regression model of F_{MAX} on D for *V. amygdalina* while the graphical illustration of the linear relationship is shown in Figure 4.10.

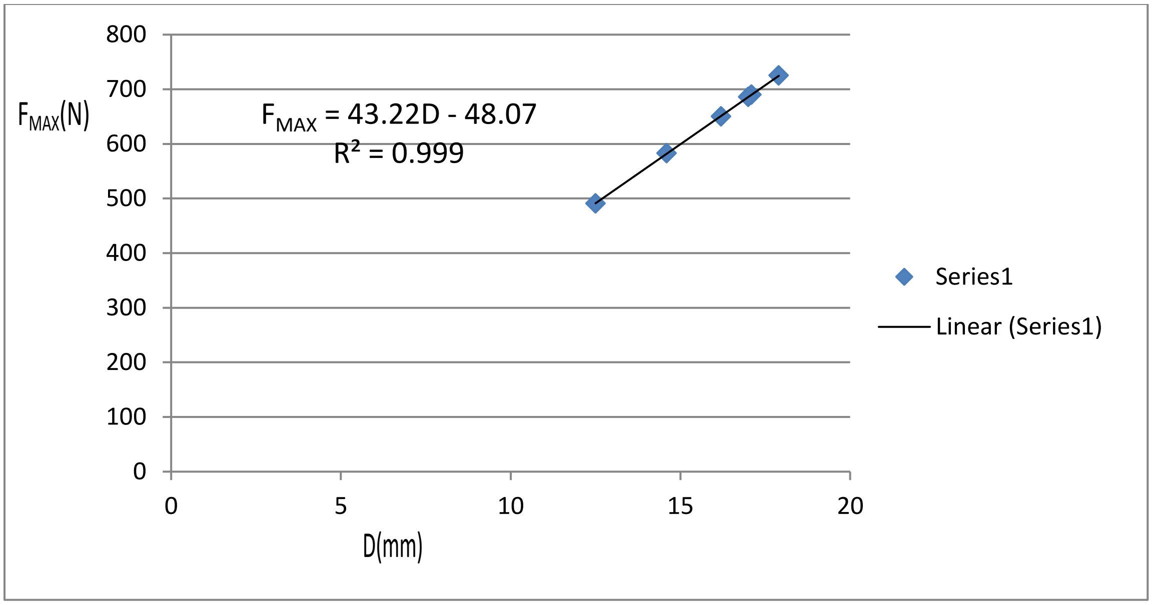

Figure 4.10: Linear regression of F_{MAX} on D for *V. amygdalina* species

For quadratic regression model, Equation (4.5) is applicable. The applicable normal equations for obtaining estimates of a_0, a_1 and a_2 are Equations (4.6a), (4.6b) and (4.6c) The terms of Equation (4.6a), Equation (4.6b) and Equation (4.6c) for *V. amygdalina* are evaluated as shown in Table 4.15.

Table 4.15: Evaluated Terms for *V. amygdalina*`s Quadratic Regression of Maximum Uprooting Force (F_{MAX}) on Stem Basal Diameter (D)

Test no	F_{MAX}	D	F_{MAX}*D	D^2	F_{MAX}*D^2	D^3	D^4
1	630	16.2	10206	262.4	165312	4251.528	68874.7536
2	610	17.1	10431	292.4	178364	5000.211	85503.6081
3	480	12.5	6000	156.3	75024	1953.125	24414.0625
4	640	14.6	9344	213.2	136448	3112.136	45437.1856
5	830	17.9	14857	320.4	265932	5735.339	102662.5681
6	634	17.0	10778	289	183226	4913	83521
Σ	3824	95.3	61616	1534	1004306	24965.339	410413.1779

The resulting normal equations with direct substitution of terms in Table 4.15 into Equation (4.6a), Equation (4.6b) and Equation (4.6c) are:

$$3824 = 6a_0 + 95.3a_1 + 1534a_2 \quad (4.21a)$$

$$61616 = 95.3a_0 + 1534a_1 + 24965.339a_2 \quad (4.21b)$$

$$1004306 = 1534a_0 + 24965.339a_1 + 410413.1779a_2 \quad (4.21c)$$

Solving for the unknown coefficients of Equation (4.21a), Equation (4.21b) and Equation (4.21c); (see matrix A.9 and matrix A.10 in Appendix A), we have:

$a_2 = 1.4292$, $a_1 = 0.9931$, $a_0 = 256.1607$.

Thus the least square quadratic equation is gotten by substituting the values of a_0, a_1 anda_2 into Equation (4.5). Thus:

$$F_{MAX} = 256.1607 + 0.9931D + 1.4292D^2 \quad (4.22)$$

The Coefficient of Determination, $r^2 = 0.878$; and $p = 0.004605$.

Equation 4.22 is the quadratic regression model of F_{MAX} on D for *V. amygdalina* while the graphical illustration of the quadratic relationship is shown in Figure 4.11.

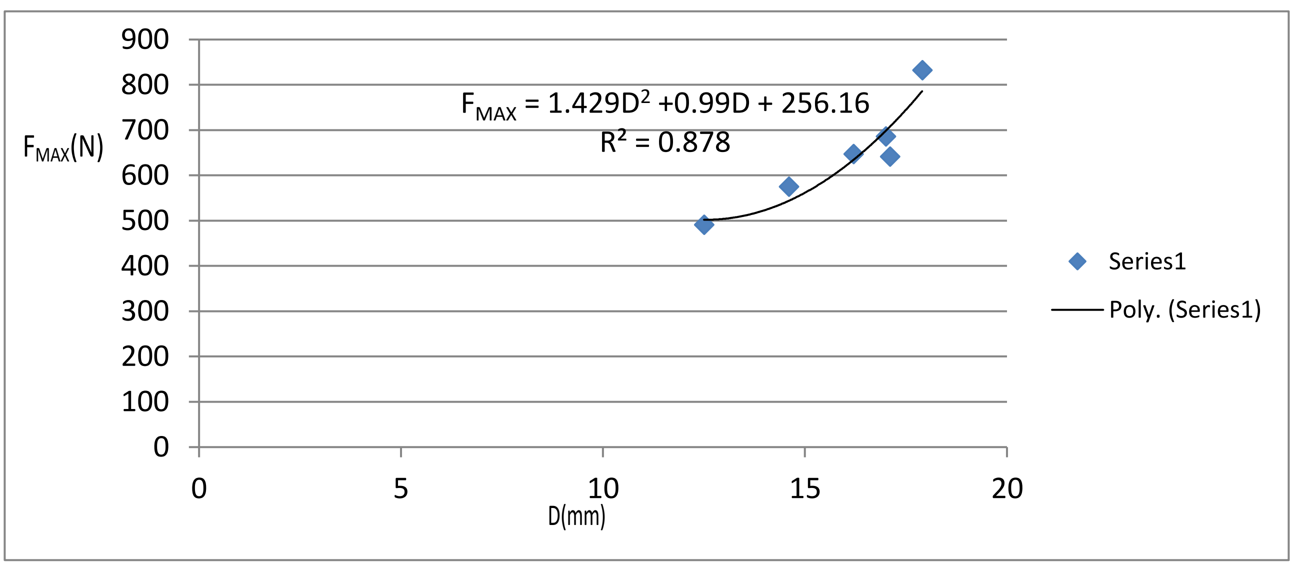

Figure 4.11: Quadratic regression of F_{MAX} on D for *V. amygdalina* species

Going further to assume a cubic polynomial regression model, Equation (4.9) is applicable. The applicable normal equations for obtaining estimates of Equation (4.9) coefficients are Equations (4.10a), (4.10b), (4.10c) and (4.10d).

The terms of Equation (4.10a), Equation (4.10b), Equation (4.10c) and Equation (4.10d) for *V. amygdalina* are evaluated as shown in Table 4.16.

Table 4.16: Evaluated Terms for *V. amygdalina*`s Cubic Polynomial Regression of Maximum Uprooting Force (F_{MAX}) on Stem Basal Diameter (D).

Test no	1	2	3	4	5	6	Σ
F_{MAX} (N)	630	610	480	640	830	634	3824
D(mm)	16.2	17.1	12.5	14.6	17.9	17.0	95.3
$F_{MAX}*D$	10206	10431	6000	9344	14857	10778	61616
D^2	262.4	292.4	156.3	213.2	320.4	289	1534
$F_{MAX}*D^2$	165312	178364	75024	136448	265932	183226	1004306
D^3	4251.528	5000.2	1953.125	3112.136	5735.339	4913	24965.339
$F_{MAX}*D^3$	2678462.64	3050128.71	937500	1991767.04	4760331.37	3114842	16533031.76
D^4	68874.7536	85503.6081	24414.0625	45437.1856	102662.5681	83521	410413.1779
D^5	1115771.008	1462111.699	305175.7813	663382.9098	1837659.969	1419857	6803958.367
D^6	18075490.33	25002110.04	3814697.266	9685390.482	32894113.44	24137569	113609370.6

The resulting equations with direct substitution of terms in Table 4.16 into Equation (4.10a), Equation (4.10b), Equation (4.10c) and Equation (4.10d) are:

$$3824 = 6a_0 + 95.3a_1 + 1534a_2 + 24965.339a_3 \quad (4.23a)$$

$$61616 = 95.3a_0 + 1534a_1 + 24965.339a_2 + 410413.1779a_3 \quad (4.23b)$$

$$1004306 = 1534a_0 + 24965.339a_1 + 410413.1779a_2 + 6803958.367a_3 \quad (4.23c)$$

$16533031 = 24965.339a_0 + 410413.1779a_1 + 6803958.367a_2 + 113609370.6a_3$ (4.23d)

Solving for the unknown coefficients of Equation (4.23a), Equation (4.23b), Equation (4.23c) and Equation (4.23d); (see matrix A.11 and matrix A.12 in Appendix A), we have:

$a_3 = -1.7643$, $a_2 = 41.7044$, $a_1 = 16.3381$, $a_0 = -2943.5381$.

Thus the least square cubic polynomial is:

$$F_{MAX} = -2943.5381 + 16.3381D + 41.7044D^2 - 1.7643D^3 \quad (4.24)$$

The Coefficient of Determination, $r^2 = 0.920$; while $p = 0.001211$.

Equation 4.24 is the cubic regression model of F_{MAX} on D for *V. amygdalina* while the graphical illustration of the cubic relationship is shown in Figure 4.12.

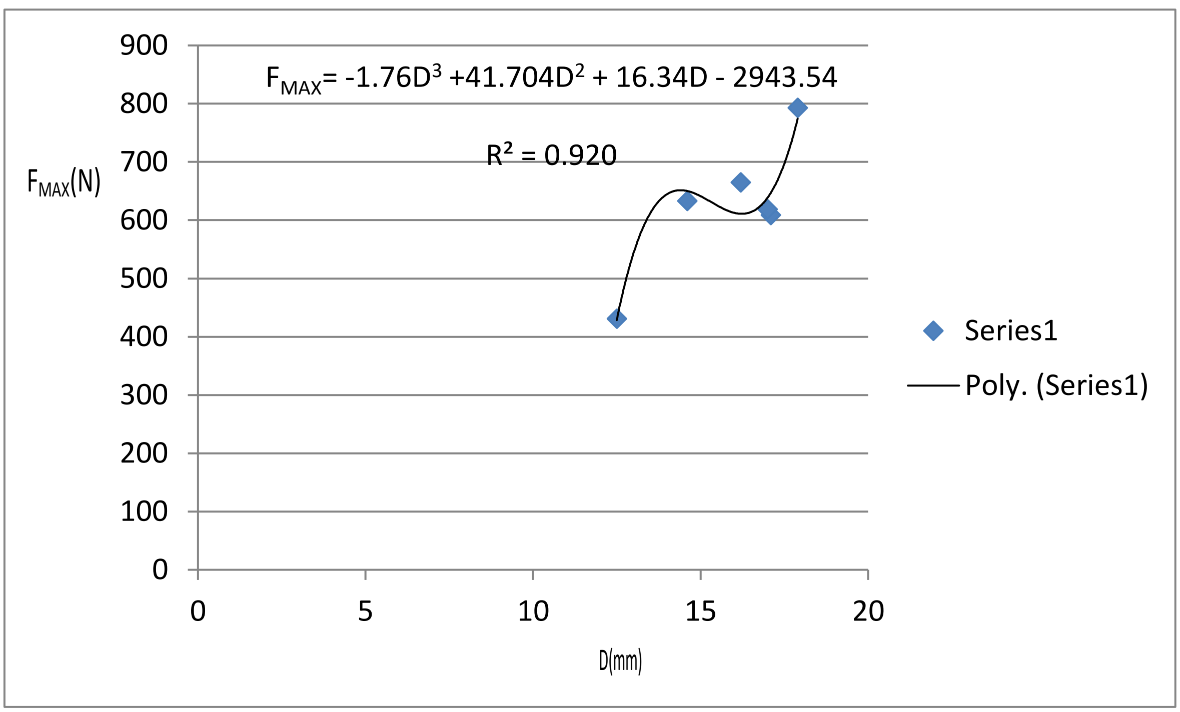

Figure 4.12: Cubic regression of F_{MAX} on D for *V. amygdalina* species

The summary of the three regression models for *V. amygdalina* species is presented in Table 4.17.

Table 4.17: Results of Regression Analysis of F_{MAX} on D for *V. amygdalina* species

Model	Equation	Coefficient of Determination(r^2)	Probability level (p)
Linear model	$F_{MAX} = 43.2D - 48.067$	0.999	0.00000037
Quadratic model	$F_{MAX} = 256.1607+0.9931D +1.4292D^2$	0.878	0.004605
Cubic polynomial model	$F_{MAX} = -2943.5381+16.3381D +41.7044D^2-1.7643D^3$	0.920	0.001211

The strength of a relationship is indicated by the Coefficient of Determination (r^2) and the significance expressed by the probability level, p. Comparing the three regression models of Table 4.17, the linear model is selected as having the best relationship between Uprooting force, F_{MAX} and basal diameter (D); for *V. amygdalina* species.

4.2.1.4 Regression Analysis of *C. dactylon*`s Maximum Uprooting Force (F_{Max}) on Stem Basal Diameter (D)

For the regression analysis of *C. dactylon*`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), the details of uprooting tests and above ground traits of *C. dactylon* is shown in Table 4.18.

Table 4.18: Above Ground Traits/Maximum Uprooting Force of *Cynodon dactylon* (Durva grass)

Test No	1	2	3	4	5	6	Mean
Plant Height H(cm)	29.5	47.0	22.2	30.0	17.4	20.0	27.68
Stem Basal Diameter D(mm)	4.0	6.5	3.9	4.5	2.0	2.15	3.84
Maximum Uprooting Force, F_{MAX}(N)	20.5	28.7	20.0	21.5	5.5	8.5	17.45

For the linear regression analysis of *C. dactylon*`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), the linear regression model is found to be of the form of Equation (4.1). The applicable normal equations for obtaining estimates of coefficients

a_0 and a_1 in Equation (4.1) are Equations (4.2a) and (4.2b). The terms of Equation (4.2a) and Equation (4.2b) for *C. dactylon* are evaluated in Table 4.19.

Table 4.19: Evaluated Terms for Linear Regression of Maximum Uprooting Force on Stem Basal Diameter for *C. dactylon*

Test No	F_{MAX}(N)	D(mm)	F_{MAX}*D	D^2 (mm^2)
1	20.5	4	82	16
2	28.7	6.5	186.6	42.25
3	20	3.9	78	15.21
4	21.5	4.5	96.75	20.25
5	5.5	2	11	4
6	8.5	2.15	18.28	4.623
Σ	104.7	23.05	472.6	102.3

The resulting normal equations with direct substitution of terms in Table 4.19 into Equation (4.2a) and Equation (4.2b) are:

$$104.7 = 6a_0 + 23.05a_1 \qquad (4.25a)$$

$$472.6 = 23.05a_0 + 102.3a_1 \qquad (4.25b)$$

Solving Equations (4.25a) and (4.25b), and substituting for a_0 and a_1 into Equation (4.1) we obtain:

$$F_{MAX} = - 2.215 + 5.121D \qquad (4.26)$$

The Coefficient of Determination, $r^2 = 0.997$; and $p = 0.00000336$.

Equation 4.26 is the linear regression model of F_{MAX} on D for *C. dactylon* while the graphical illustration of the linear relationship is shown in Figure 4.13.

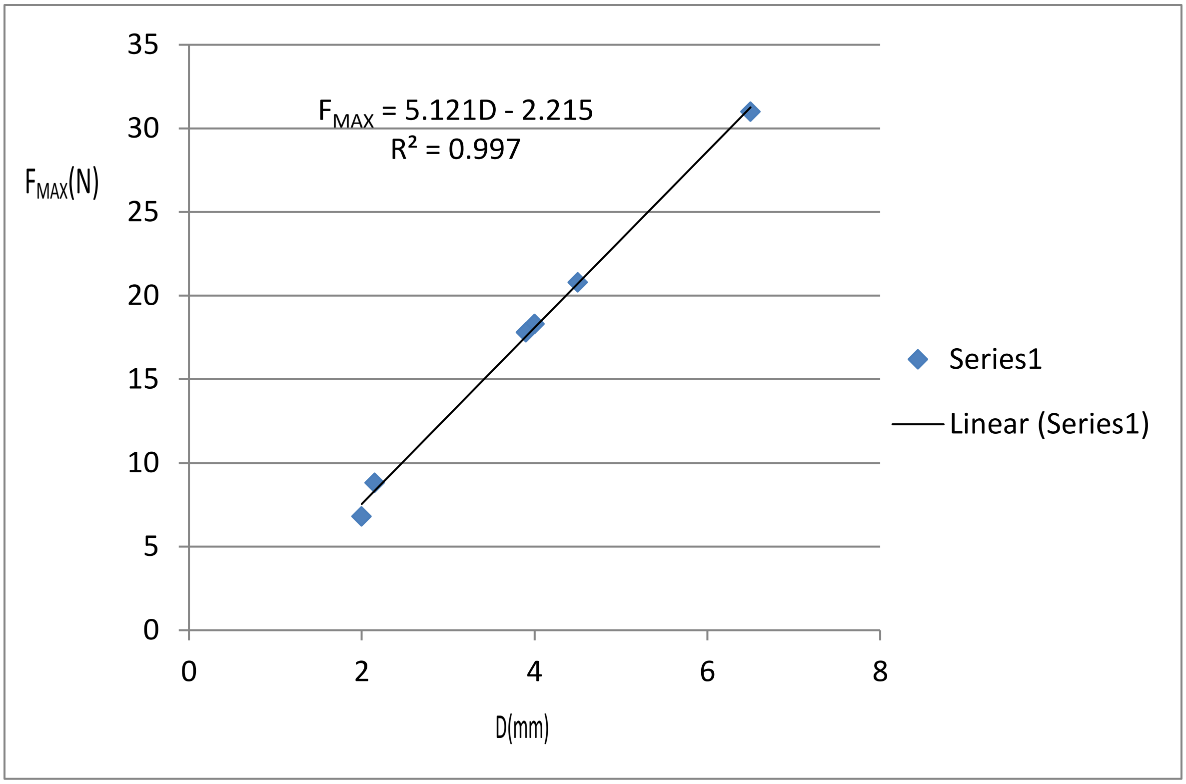

Figure 4.13: Linear regression of F_{MAX} on D for *C. dactylon* species

Assuming Quadratic regression model of the form of Equation (4.5) and repeating the procedure outlined for Quadratic regression model in section 4.2.3; after generating similar table to Table 4.14 using the data of Table 4.17 instead of Table 4.12; we obtain that:

$$F_{MAX} = -1.8534 + 4.9027D + 0.02749D^2 \quad (4.27)$$

The Coefficient of Determination, $r^2 = 0.994$; while $p = 0.00001337$.

Equation 4.27 is the quadratic regression model of F_{MAX} on D for *C. dactylon* while the graphical illustration of the quadratic relationship is shown in Figure 4.14.

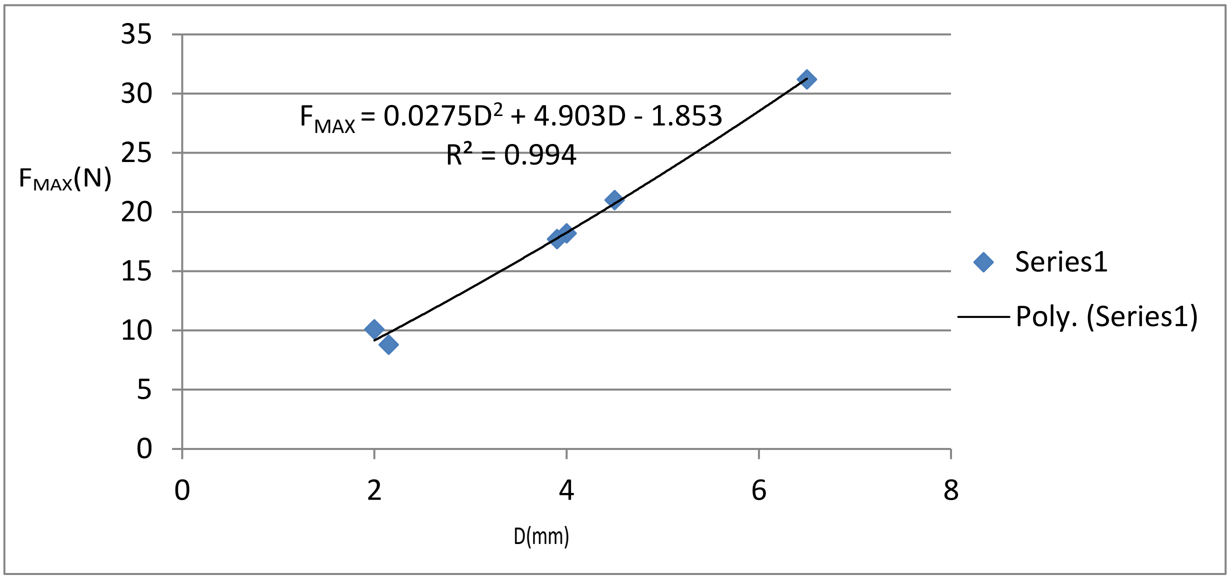

Figure 4.14: Quadratic regression of F_{MAX} on D for *C. dactylon* species

Going further to assume a cubic polynomial regression model of the form of Equation (4.9) and repeating the procedure outlined for cubic polynomial model in section 4.2.3; after generating similar table to Table 4.16 using the data of Table 4.18 instead of Table 4.13; we obtain that:

$$F_{MAX} = -159.7845+42.7652D +11.7911D^2 - 2.2526D^3 \quad (4.28)$$

The Coefficient of Determination, $r^2 = 0.942$; while $p = 0.00115$.

Equation 4.28 is the cubic regression model of F_{MAX} on D for *C. dactylon* while the graphical illustration of the cubic relationship is shown in Figure 4.15.

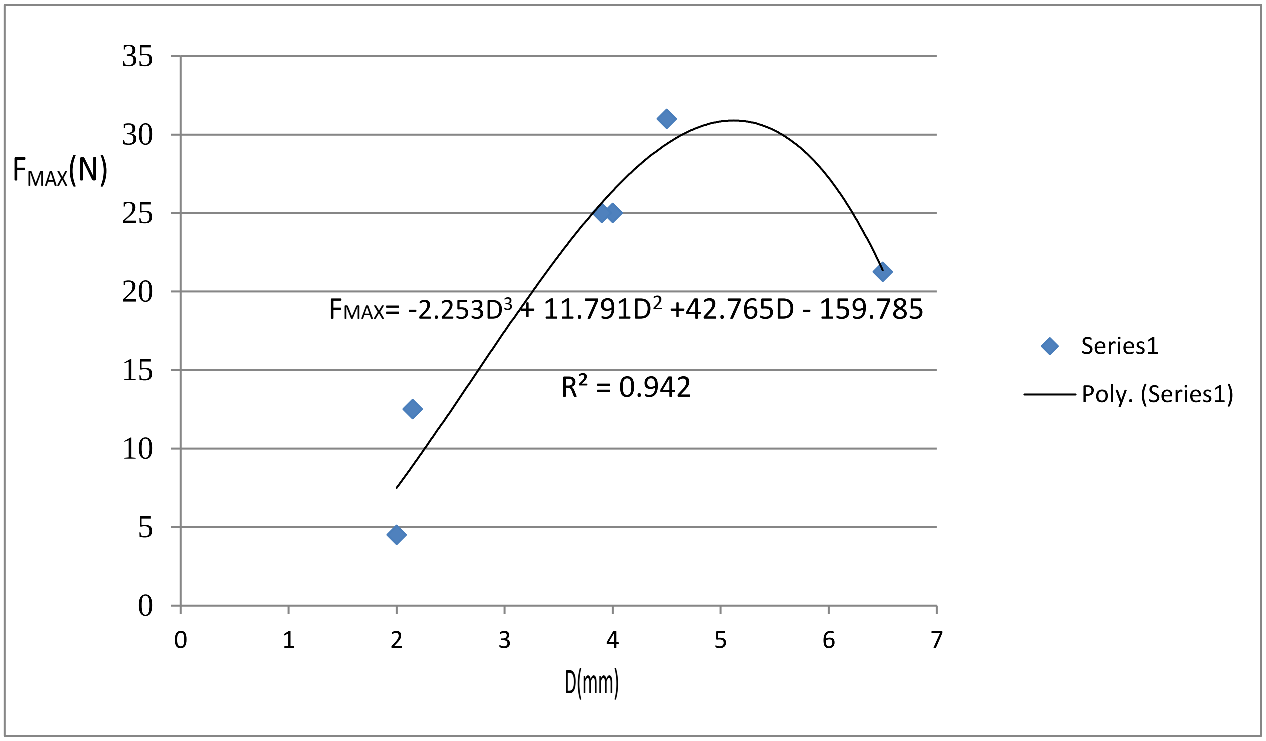

Figure 4.15: Cubic regression of F_{MAX} on D for *C. dactylon* species

The summary of the three regression models for *C. dactylon* species is presented in Table 4.20.

Table 4.20: Results of Regression Analysis of F_{MAX} D for *C. dactylon* species

Model	Equation	Coefficient of Determination (r^2)	Probability level (p)
Linear model	$F_{MAX} = 5.121D – 2.215$	0.997	0.00000336
Quadratic model	$F_{MAX} = -1.8534+4.9027D +0.02749D^2$	0.994	0.00001337
Cubic polynomial model	$F_{MAX} = -159.7845+42.7652D +11.7911D^2-2.2526D^3$	0.942	0.00115

The strength of a relationship is indicated by the Coefficient of Determination (r^2) and the significance expressed by the probability level, p. Comparing the three regression models of Table 4.20, there is high linear relationship between Uprooting force, F_{MAX} and basal diameter (D); for *C. dactylon* species.

4.2.1.5 Regression Analysis of P. purpureum`s Maximum Uprooting Force (F_{Max}) on Stem Basal Diameter (D)

For the regression analysis of *P. purpureum*`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), the details of uprooting tests and above ground traits of *P. purpureum* is shown in Table 4.21.

Table 4.21: Above Ground Traits/Maximum Uprooting Force of *Pennistum purpureum* (Elephant grass)

Test No	1	2	3	4	5	6	Mean
Plant Height H(cm)	57.0	25.0	32.0	28.0	35.0	27.5	34.1
Stem Basal Diameter D(mm)	7.2	6.0	7.0	6.5	6.8	6.5	6.67
Maximum Uprooting Force, F_{MAX}(N)	68.8	28.3	42.5	34.0	35.4	32.6	40.27

For the linear regression analysis of *P. purpureum*`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), the linear regression model is found to be of the form of Equation (4.1) and the applicable normal equations for obtaining estimates of coefficients a_0 and a_1 of Equation (4.1) are Equations (4.2a) and (4.2b).

The terms of Equations (4.2a) and (4.2b) for *P. purpureum* are evaluated as shown in Table 4.22.

Table 4.22: Evaluated Terms for Linear Regression of F_{MAX} on D for *P. purpureum*

Test No	F_{MAX}(N)	D(mm)	$F_{MAX}*D$	D^2 (mm^2)
1	68.8	7.2	495.4	51.84
2	28.3	6	169.8	36
3	42.5	7	297.5	49
4	34	6.5	221	42.25
5	35.4	6.8	240.7	46.24
6	32.6	6.5	211.9	42.25
Σ	241.6	40	1636	267.6

The resulting normal equations with direct substitution of terms in Table 4.22 into Equation (4.2a) and Equation (4.2b) are:

$241.6 = 6a_0 + 40a_1$ (4.29a)

$1636 = 40a_0 + 267.6a_1$ (4.29b)

Solving Equations (4.29a) and (4.29b), and substituting for a_0 and a_1 into Equation (4.1) we obtain:

$F_{MAX} = -128.541 + 25.32D$ (4.30)

The Coefficient of Determination, $r^2 = 0.996$; while $p = 0.00000596$.

Equation 4.30 is the linear regression model of F_{MAX} on D for *P. purpureum* while the graphical illustration of the linear relationship is shown in Figure 4.16.

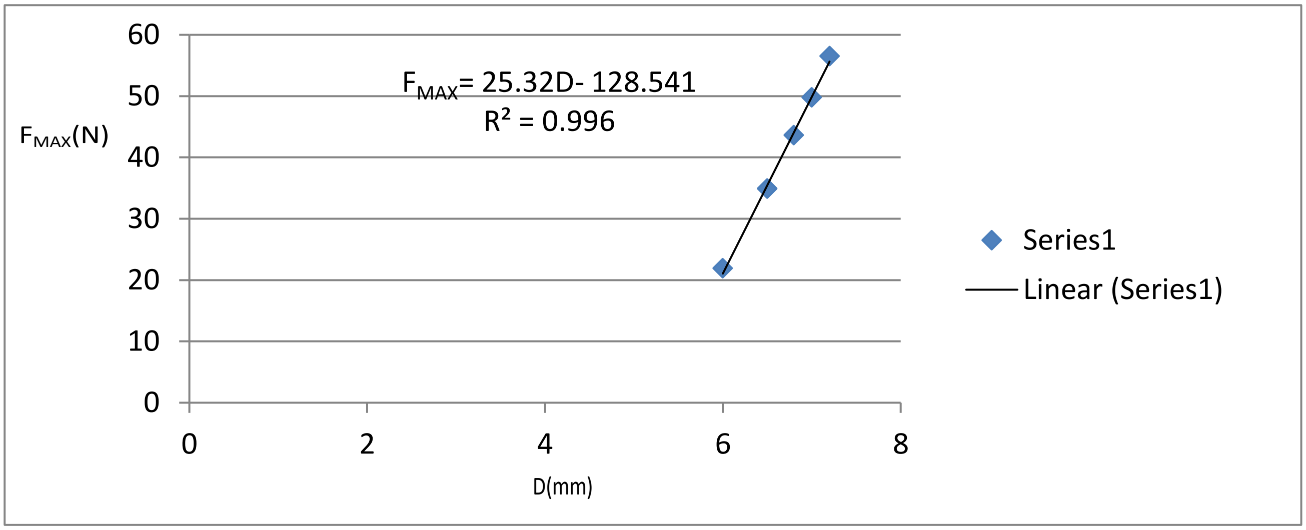

Figure 4.16: Linear regression of F_{MAX} on D for *P. purpureum* species

Assuming Quadratic regression model of the form of Equation (4.5) and repeating the procedure outlined for Quadratic regression model in section 4.2.3; after generating similar table to Table 4.14 using the data of Table 4.20 instead of Table 4.12; we obtain that:

$$F_{MAX} = 11.6111 - 20.7449D + 3.7434D^2 \quad (4.31)$$

The Coefficient of Determination, $r^2 = 0.981$; while $p = 0.0001312$.

Equation 4.31 is the quadratic regression model of F_{MAX} on D for *P. purpureum* while the graphical illustration of the quadratic relationship is shown in Figure 4.17.

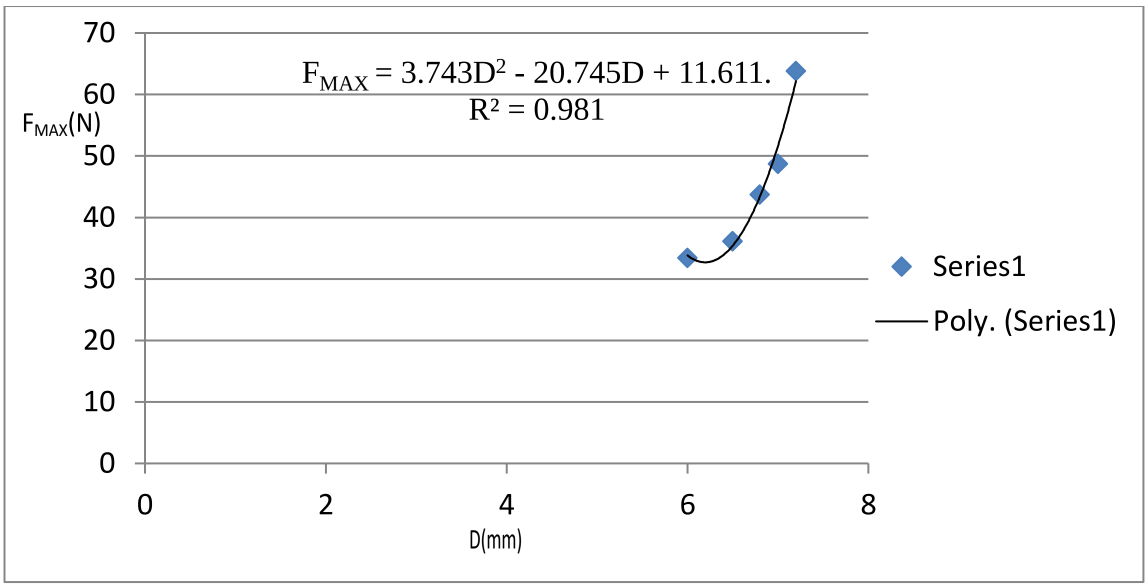

Figure 4.17: Quadratic regression of F_{MAX} on D for *P. purpureum* species

Going further to assume a cubic polynomial regression model of the form of Equation (4.9) and repeating the procedure outlined for cubic polynomial model in section 4.2.3; after generating similar table to Table 4.14 using the data of Table 4.20 instead of Table 4.12; we obtain that:

$$F_{MAX} = -170.4689 - 10.4568D + 13.0416D^2 - 1.0063D^3 \quad (4.32)$$

The Coefficient of Determination, $r^2 = 0.987$; and $p = 0.00006203$.

Equation 4.32 is the cubic regression model of F_{MAX} on D for *P. purpureum* while the graphical illustration of the cubic relationship is shown in Figure 4.18.

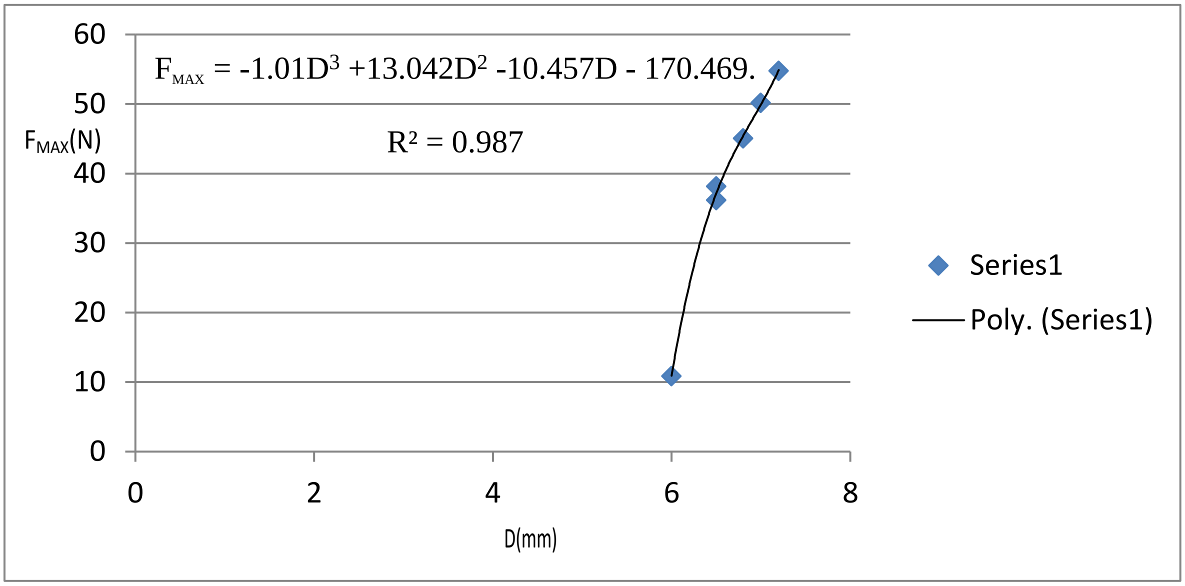

Figure 4.18: Cubic regression of F_{MAX} on D for *P. purpureum* species

The summary of the three regression models for *P. purpureum* species is presented in Table 4.23.

Table 4.23: Results of Regression Analysis F_{MAX} on D for *P. purpureum* species

Model	Equation	Coefficient of Determination (r^2)	Probability level (p)
Linear model	$F_{MAX} = 25.32D – 128.541$	0.996	0.00000596
Quadratic model	$F_{MAX} = 11.6111-20.7449D +3.743D^2$	0.981	0.0001312
Cubic polynomial model	$F_{MAX} = -170.4689-10.4568D +13.0416D^2-1.0063D^3$	0.987	0.00006203

The strength of a relationship is indicated by the Coefficient of Determination (r^2) and the significance expressed by the probability level, p. Comparing the three regression models of Table 4.23, there is higher linear relationship between Uprooting force, F_{MAX} and basal diameter (D); for *P. purpureum* species.

4.2.1.6 Regression Analysis of *S. officinarium*`s Maximum Uprooting Force (F_{Max}) on its Stem Basal Diameter (D)

For the regression analysis of *S. officinarium*`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), the details of uprooting tests and above ground traits of *S. officinarium* is shown in Table 4.24.

Table 4.24: Above Ground Traits/Maximum Uprooting Force of *Saccharum officinarum* (Cane grass)

Test No	1	2	3	4	5	6	Mean
Plant Height H(cm)	75.0	50.0	45.0	65.0	48.5	83.0	61.08
Stem Basal Diameter D(mm)	15.5	11.5	10.0	12.5	10.6	16.9	12.83
Maximum Uprooting Force, F_{MAX}(N)	180.0	125.0	95.0	140.0	184.9	246.0	161.82

For the linear regression analysis of S. officinarium`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), the linear regression model is found to be of the form of Equation (4.1). The applicable normal equations for obtaining estimates of the coefficients a_0 and a_1 of Equation (4.1) are Equations (4.2a) and (4.2b). The terms of Equations (4.2a) and (4.2b) for *S. officinarium* are evaluated as shown in Table 4.25.

Table 4.25: Evaluated Terms for Linear Regression of Maximum Uprooting Force on Stem Basal Diameter for *S. officinarium*

Test No	F_{MAX}(N)	D(mm)	$F_{MAX}*D$	D^2 (mm^2)
1	180	15.5	2790	240.3
2	125	11.5	1438	132.3
3	95	10	950	100
4	140	12.5	1750	156.3
5	184.9	10.6	1960	112.4
6	246	16.9	4157	285.6
Σ	970.9	77	13045	1027

The resulting normal equations with direct substitution of terms in Table 4.25 into Equation (4.2a) and Equation (4.2b) are:

$$970 = 6a_0 + 77a_1 \qquad (4.33a)$$

$$13045 = 77a_0 + 1027a_1 \qquad (4.33b)$$

Solving Equations (4.33a) and (4.33b), and substituting for a_0 and a_1 into Equation (4.1) we obtain:

$$F_{MAX} = -31.409 + 15.057D \qquad (4.34)$$

The Coefficient of Determination, $r^2 = 0.90$; while $p = 0.003197$.

For quadratic regression analysis of F_{MAX} on D for *S. officinarium* species, the form of the regression model is Equation (4.5) and repeating the procedure outlined for Quadratic regression model in section 4.2.3; after generating similar table to Table 4.15 using the data of Table 4.24 instead of Table 4.13; we obtain that:

$$F_{MAX} = 77.5998 - 2.2642D + 0.6609D^2 \qquad (4.35)$$

The Coefficient of Determination, $r^2 = 0.65$; and $p = 0.02776$.

Going further to assume a cubic polynomial regression model of the form of Equation (4.9) and repeating the procedure outlined for cubic polynomial model in section 4.2.3; after generating similar table to Table 4.16 using the data of Table 4.24 instead of Table 4.13; we obtain that:

$$F_{MAX} = -170.4689 + 11.09D - 3.0132D^2 + 0.1537D^3 \qquad (4.36)$$

The Coefficient of Determination, $r^2 = 0.69$; while $p = 0.022921$.

The summary of the three regression models for *S. officinarium* species is presented in Table 4.26.

Table 4.26: Results of Regression Analysis of F_{MAX} on D for *S. officinarium* species

Model	Equation	Coefficient of Determination (r^2)	Probability level (p)
Linear model	$F_{MAX} = 15.057D – 31.409$	0.90	0.003197
Quadratic model	$F_{MAX} = 77.5998-2.2642D +0.6609D^2$	0.65	0.02776
Cubic polynomial model	$F_{MAX} = -170.4689+11.09D - 3.012D^2+0.1537D^3$	0.69	0.022921

The strength of a relationship is indicated by the Coefficient of Determination (r^2) and the significance expressed by the probability level, p. Comparing the three regression models of Table 4.26, there is higher linear relationship between Uprooting force, F_{MAX} and basal diameter (D); for *S. officinarium* species.

4.2.1.7 Regression Analysis of *M. indica*`s Maximum Uprooting Force (F_{Max}) on Stem Basal Diameter (D)

For the regression analysis of *M. indica*`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), the details of uprooting tests and above ground traits of *M. indica* species is shown in Table 4.27.

Table 4.27: Above Ground Traits/Maximum Uprooting Force of *Mangifera indica* (Juvenile Mango tree)

Test No	1	2	3	4	5	6	Mean
Plant Height H(cm)	87.5	40.0	65.0	60.0	36.3	38.0	54.5
Stem Basal Diameter D(mm)	18.6	14.5	18.2	17.5	10.5	13.0	15.38
Maximum Uprooting Force, F_{MAX}(N)	837.0	285.0	450.0	405.0	225.0	276.0	418.0

For the linear regression analysis of *M. indica*`s maximum uprooting force (F_{Max}) on its stem basal diameter (D), the linear regression model is found to be of the form of

Equation (4.1).The applicable normal equations for obtaining estimates of the values of the coefficients a_0 and a_1 in Equation (4.1) are Equation (4.2a) and (4.2b)

The terms of Equations (4.2a) and (4.2b) for *M. indica* are evaluated as shown in Table 4.28.

Table 4.28: Evaluated Terms for Linear Regression of Maximum Uprooting Force on Stem Basal Diameter for *M. indica*

Test No	F_{MAX}(N)	D(mm)	$F_{MAX}*D$	D^2 (mm^2)
1	837	18.6	15568	346
2	285	14.5	4133	210.3
3	450	18.2	8190	331.2
4	405	17.5	7088	306.3
5	225	10.5	2363	110.3
6	276	12	3312	144
Σ	2478	91.3	40653	1448

The resulting normal equations with direct substitution of terms in Table 4.28 into Equation (4.2a) and Equation (4.2b) are:

$$2478 = 6a_0 + 91.3a_1 \quad (4.37a)$$

$$40653 = 91.3a_0 + 1448a_1 \quad (4.37b)$$

Solving Equations (4.37a) and (4.37b), and substituting for a_0 and a_1 into Equation (4.1) we obtain:

$$F_{MAX} = - 350.878 + 50.199D \quad (4.38)$$

The Coefficient of Determination, $r^2 = 0.998$; while $p = 0.000001495$.

Equation 4.38 is the linear regression model of F_{MAX} on D for *M. indica* while the graphical illustration of the linear relationship is shown in Figure 4.19.

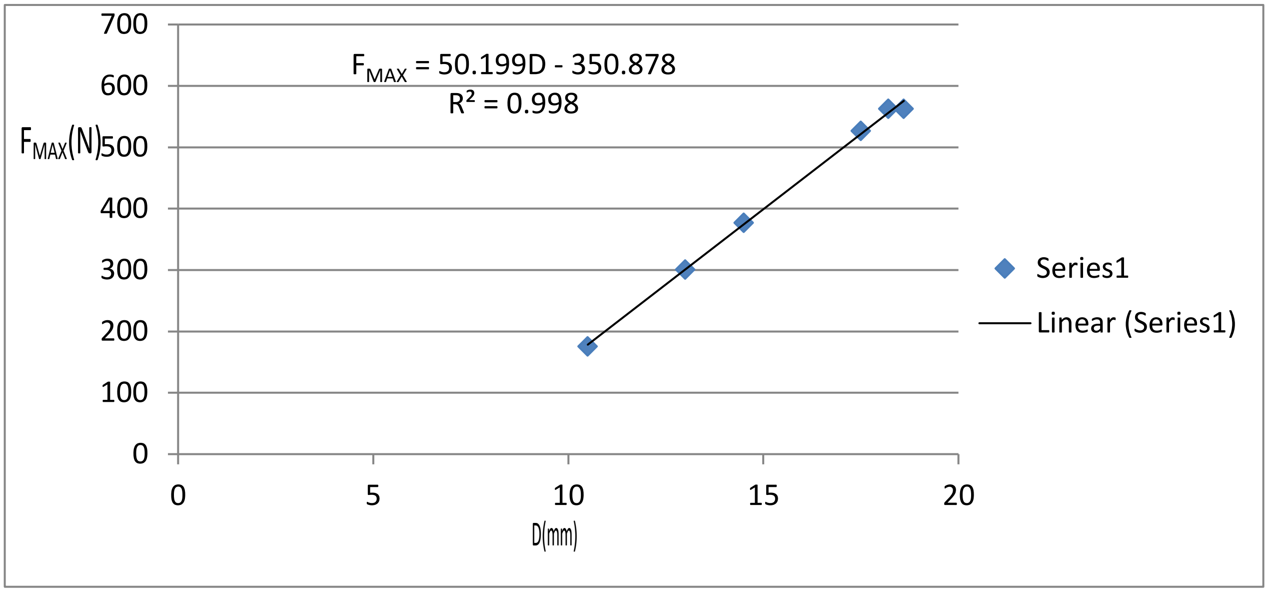

Figure 4.19: Linear regression of F_{MAX} on D for *M. indica* species.

Assuming Quadratic regression model of the form of Equation (4.5) and repeating the procedure outlined for Quadratic regression model in section 4.2.3; after generating similar table to Table 4.15 using the data of Table 4.27 instead of Table 4.13; we obtain that:

$$F_{MAX} = 1746.4636 - 249.6391D + 10.215D^2 \quad (4.39)$$

The Coefficient of Determination, $r^2 = 0.977$; and $p = 0.000191$.

Equation 4.39 is the quadratic regression model of F_{MAX} on D for *M. indica* while the graphical illustration of the quadratic relationship is shown in Figure 4.20.

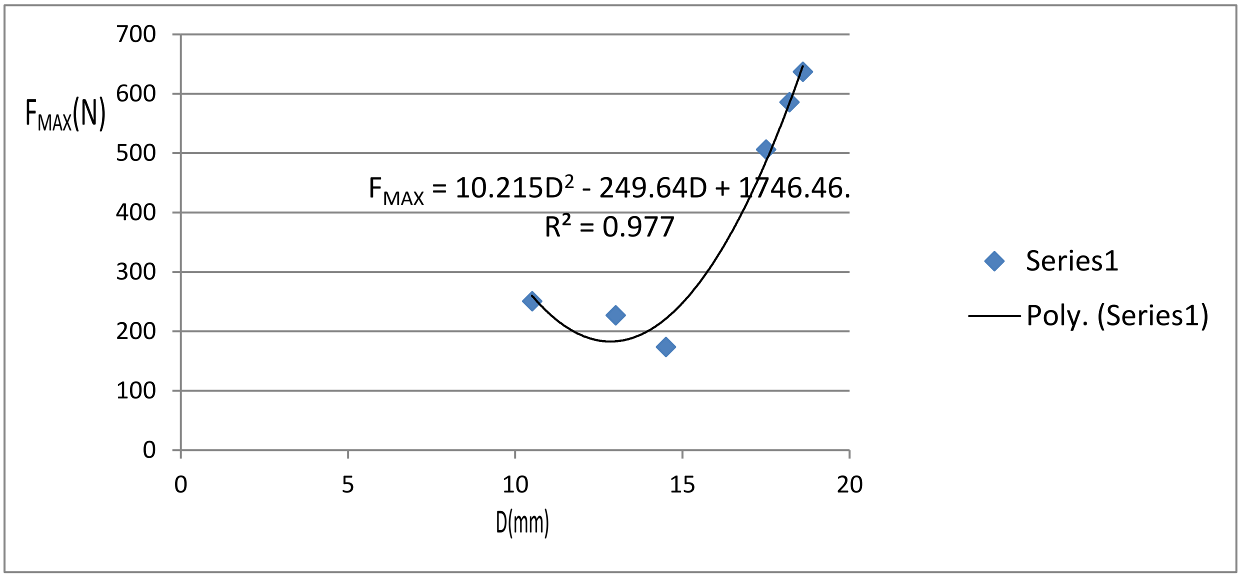

Figure 4.20: Quadratic regression of F_{MAX} on D for *M. indica* species.

For cubic polynomial regression model, Equation (4.9) is applicable.

Repeating the procedure outlined for cubic polynomial model in section 4.2.3; after generating similar table to Table 4.16 using the data of Table 4.27 instead of Table 4.13; we obtain that:

$$F_{MAX} = 637.1325+48.5468D -14.8658D^2+0.6629D^3. \quad (4.40)$$

The Coefficient of Determination, $r^2 = 0.928$; and $p = 0.001731$.

Equation 4.40 is the cubic regression model of F_{MAX} on D for *M. indica* while the graphical illustration of the cubic relationship is shown in Figure 4.21.

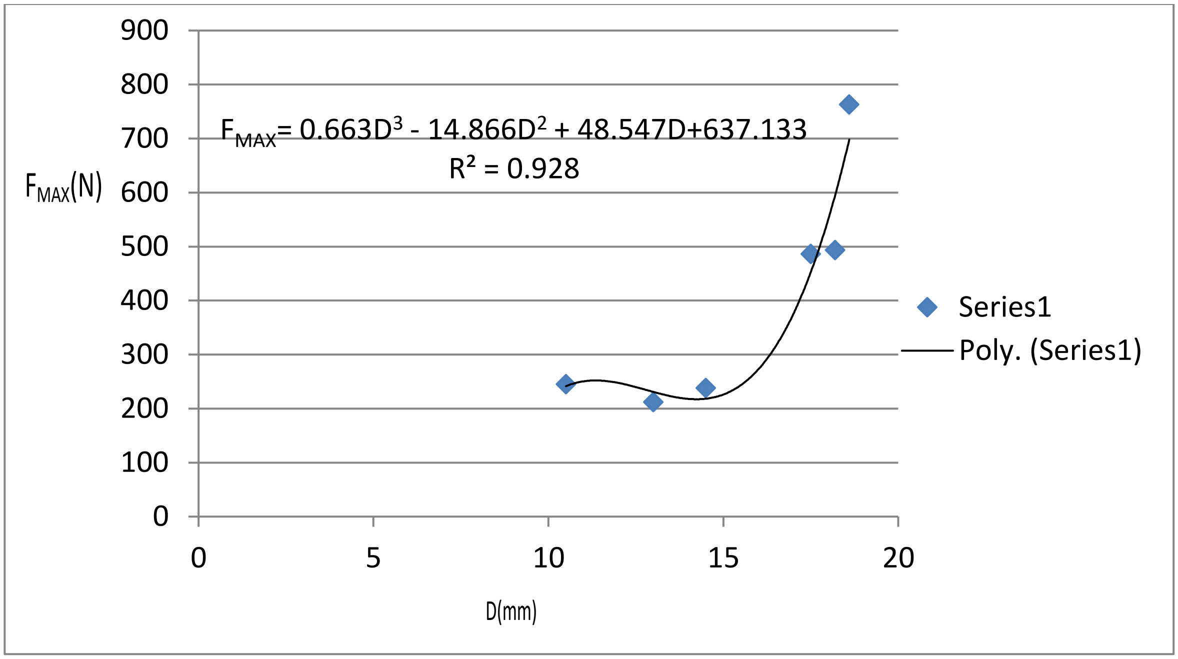

Figure 4.21: Cubic regression of F_{MAX} on D for *M. indica* species.

The summary of the three regression models for *M. indica* species is presented in Table 4.29.

Table 4.29: Results of Regression Analysis of F_{MAX} on D for *M. indica* species

Model	Equation	Coefficient of Determination (r^2)	Probability level (p)
Linear model	$F_{MAX} = 50.199D - 350.878$	0.998	0.000001495
Quadratic model	$F_{MAX} = 1746.4636 - 249.6391D + 10.215D^2$	0.977	0.000191
Cubic polynomial model	$F_{MAX} = 637.1325 + 48.5468D - 14.8658D^2 - 0.6629D^3$	0.928	0.001731

The strength of a relationship is indicated by the Coefficient of Determination (r^2) and the significance expressed by the probability level, p. Comparing the three regression models of Table 4.29, there is higher linear relationship between Uprooting force, F_{MAX} and basal diameter (D); for *M. indica* species.

4.2.1.8 Regression Analysis of *A. occidentale*`s Maximum Uprooting Force (F_{Max}) on Stem Basal Diameter (D)

For the regression analysis of *A. occidentale*`s maximum uprooting force (F_{Max}) on stem basal diameter (D), the details of uprooting tests and above ground traits of *A. occidentale* species is shown in Table 4.30.

Table 4.30: Above Ground Traits/Maximum Uprooting Force of *Anacardium occidentale*(Juvenile Cashew tree)

Test No	1	2	3	4	5	6	Mean
Plant Height H(cm)	35.0	40.0	55.0	75.0	32.0	34.5	45.25
Stem Basal Diameter D(mm)	12.3	11.5	16.2	18.0	11.0	11.2	13.37
Maximum Uprooting Force, F_{MAX}(N)	300.0	225.0	270.0	855.0	195.0	210.0	342.5

For the linear regression analysis of *A. occidentale*`s maximum uprooting force (F_{Max}) on stem basal diameter (D), the linear regression model is of the form of Equation (4.1). The applicable normal equations for obtaining estimates of a_0 and a_1 contained in Equation (4.1) are Equation (4.2a) and (4.2b). The terms of Equations (4.2a) and (4.2b) for *A. occidentale* are evaluated as shown in Table 4.31.

Table 4.31: Evaluated Terms for Linear Regression of Maximum Uprooting Force on Stem Basal Diameter for *A. occidentale*

Test No	F_{MAX}(N)	D(mm)	$F_{MAX}*D$	D^2 (mm^2)
1	300	12.3	3690	151.3
2	225	11.5	2588	132.3
3	270	16.2	4374	262.4
4	855	18	15390	324
5	195	11	2145	121
6	210	11.2	2352	125.4
Σ	2055	80.2	30539	1116

The resulting normal equations with direct substitution of terms in Table 4.31 into Equation (4.2a) and Equation (4.2b) are:

$$2025 = 6a_0 + 80.2a_1 \tag{4.41a}$$

$$30539 = 80.2a_0 + 1116a_1 \tag{4.41b}$$

Solving Equations (4.41a) and (4.41b), and substituting for a_0 and a_1 into Equation (4.1) we obtain:

$$F_{MAX} = -\,590.493 + 69.8D \tag{4.42}$$

The Coefficient of Determination, $r^2 = 0.999$; and $p = 0.00000037$.

Equation 4.42 is the linear regression model of F_{MAX} on D for *A. occidentale* while the graphical illustration of the linear relationship is shown in Figure 4.22.

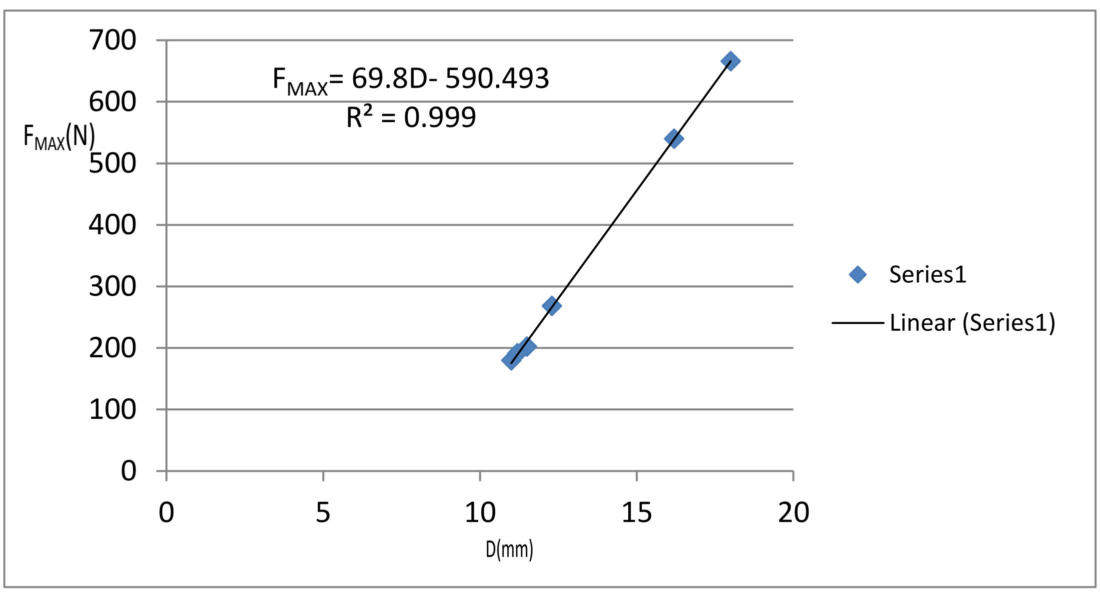

Figure 4.22: Linear regression of F_{MAX} on D for *A. occientale* species.

For quadratic regression model, Equation (4.5) is applicable.

Repeating the procedure outlined for Quadratic regression model in section 4.2.3; after generating similar table to Table 4.15 using the data of Table 4.30 instead of Table 4.13; we obtain that:

$$F_{MAX} = 7788.8039 – 1142.76D + 42.0743D^2 \quad (4.43)$$

The Coefficient of Determination, $r^2 = 0.980$; while $p = 0.0001451$.

Equation 4.43 is the quadratic regression model of F_{MAX} on D for *A. occidentale* while the graphical illustration of the quadratic relationship is shown in Figure 4.23.

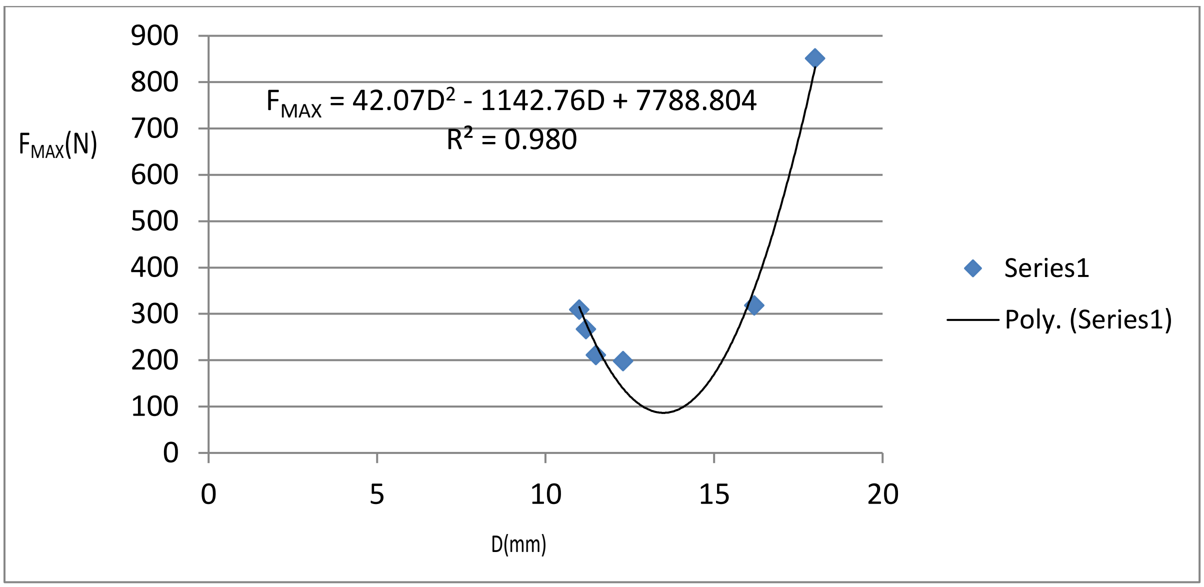

Figure 4.23: Quadratic regression of F_{MAX} on D for *A. occientale* species.

For a cubic polynomial regression model of *A. occidentale*, Equation (4.9) is applicable. Repeating the procedure outlined for cubic polynomial model in section 4.2.3; after generating similar table to Table 4.16 using the data of Table 4.30 instead of Table 4.13; we obtain that:

$$F_{MAX} = 2673.5710-212.4646D -11.0297D^2 +0.9485D^3 \quad (4.44)$$

The Coefficient of Determination, $r^2 = 0.998$; and $p = 0.000001495$.

Equation 4.44 is the cubic regression model of F_{MAX} on D for *A. occidentale* while the graphical illustration of the cubic relationship is shown in Figure 4.24.

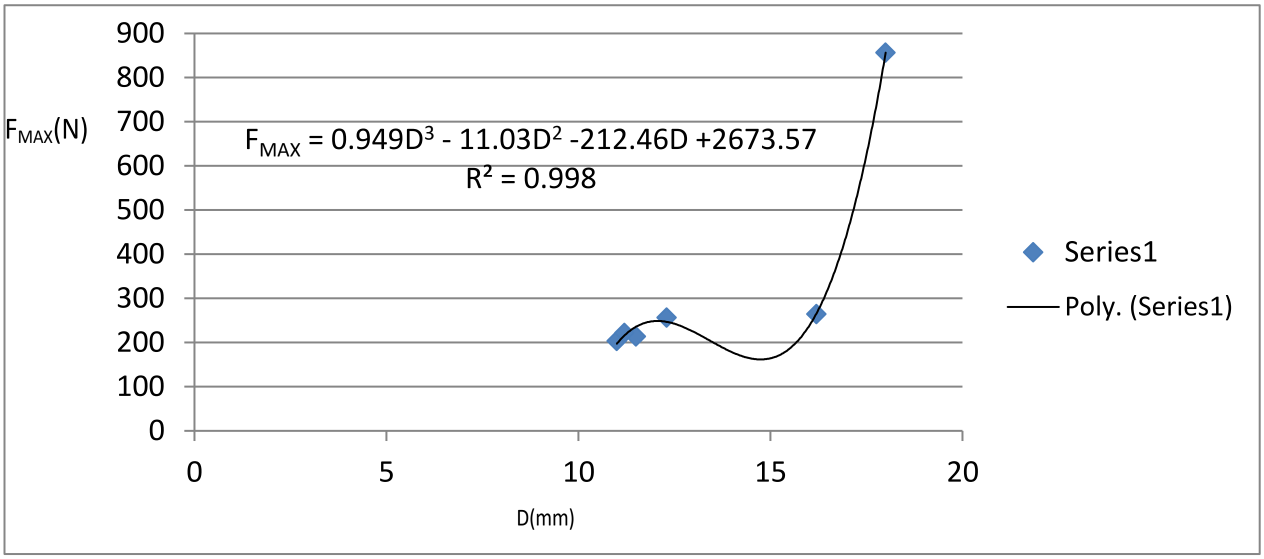

Figure 4.24: Cubic regression of F_{MAX} on D for *A. occientale* species.

The summary of the three regression models for *A. occidentle* species is presented in Table 4.32.

Table 4.32: Results of Regression Analysis of F_{MAX} on D for *A. occidentale* species

Model	Equation	Coefficient of Determination (r^2)	Probability level (p)
Linear model	F_{MAX} = 69.8D – 590.493	0.999	0.00000037
Quadratic model	F_{MAX} = 7788.8039-1142.76D +42.0743D^2	0.980	0.0001451
Cubic polynomial model	F_{MAX} = 2673.5710-212.4646D -11.0297D^2+0.9485D^3	0.998	0.000001495

The strength of a relationship is indicated by the Coefficient of Determination (r^2) and the significance expressed by the probability level, p. Comparing the three regression models of Table 4.32, linear model is preferred as the best relationship between Uprooting force, F_{MAX} and basal diameter (D); for *A. occidentale* species.

4.2.1.9 Regression Analysis of *A. indica*`s Maximum Uprooting Force (F_{Max}) on Stem Basal Diameter (D)

For the regression analysis of *A. indica*`s maximum uprooting force (F_{Max}) on stem basal diameter (D), the details of uprooting tests and above ground traits of *A. indica* species are shown in Table 4.33.

Table 4.33: Above Ground Traits/Maximum Uprooting Force of *Azadirachta indica*

Test No	1	2	3	4	5	6	Mean
Plant Height H(cm)	68.5	60.0	35.0	40.5	60.0	26.5	48.5
Stem Basal Diameter D(mm)	19.5	19.0	15.5	17.5	17.3	12.0	16.8
Maximum Uprooting Force, F_{MAX}(N)	741.0	561	525.0	570	540.0	195	432.0

For the linear regression analysis of *A. indica*`s maximum uprooting force (F_{Max}) on stem basal diameter (D), Equation (4.1) is applicable. The applicable normal equations for obtaining estimates of a_0 and a_1 in Equation (4.1) are Equations (4.2a) and (4.2b).

The terms of equations (4.2a) and (4.2b) for *A. indica* are evaluated as shown in Table 4.34.

Table 4.34: Evaluated Terms for Linear Regression of Maximum Uprooting Force on Stem Basal Diameter for *A. indica*

Test No	F_{MAX}(N)	D(mm)	$F_{MAX}*D$	D^2 (mm^2)
1	741	19.5	14450	380.3
2	561	19	10659	361
3	525	15.5	8138	240.3
4	570	17.5	9975	306.3
5	540	17.3	9342	299.3
6	195	12	2340	144
Σ	3132	100.8	54903	1731

The resulting normal equations with direct substitution of terms in Table 4.34 into equation (4.2a) and equation (4.2b) are:

$$3132 = 6a_0 + 100.8a_1 \qquad (4.45a)$$

$$54903 = 100.8a_0 + 1731a_1 \qquad (4.45b)$$

Solving Equations (4.45a) and (4.45b), and substituting for a_0 and a_1 into Equation (4.1) we obtain:

$$F_{MAX} = - 500.22 + 60.85D \qquad (4.46)$$

The Coefficient of Determination, $r^2 = 0.999$; while $p = 0.00000037$.

For quadratic regression model, Equation (4.5) is applicable.

The applicable normal equations for obtaining estimates of a_0, a_1 and a_2 in Equation (4.1) are Equations (4.6a), (4.6b) and (4.6c). The terms of Equations (4.6a), (4.6b) and (4.6c) for *A. indica* are evaluated as shown in Table 4.35.

Table 4.35: Evaluated Terms for *A. indica*`s Quadratic Regression of Maximum Uprooting Force (F_{MAX}) on Stem Basal Diameter (D)

Test No	F_{MAX}	D	$F_{MAX}*D$	D^2	$F_{MAX}*D^2$	D^3	D^4
1	741	19.5	14450	380.3	281802.3	7414.875	144590.0625
2	561	19	10659	361	202521	6859	130321
3	525	15.5	8138	240.3	126157.5	3723.875	57720.0625
4	570	17.5	9975	306.3	174591	5359.375	93789.0625
5	540	17.3	9342	299.3	161622	5177.717	89574.5041
6	195	12	2340	144	28080	1728	20736
Σ	3132	100.8	54903	1731	974773.8	30262.842	536730.6916

The resulting normal equations with direct substitution of terms in Table 4.35 into Equation (4.6a), Equation (4.6b) and Equation (4.6c) are:

$3132 = 6a_0 + 100.8a_1 + 1731a_2$ (4.47a)

$54903 = 100.8a_0 + 1731a_1 + 30262.842a_2$ (4.47b)

$974773.8 = 1731a_0 + 30262.842a_1 + 536730.6916a_2$ (4.47c)

Solving for the unknown coefficients of Equation (4.47a), Equation (4.47b) and Equation (4.47c), (see matrix A.13 and matrix A.14 in Appendix A), we have:

$a_2 = -5.5244$, $a_1 = 234.7156$, $a_0 = -1827.4327$.

Thus the least square quadratic equation is gotten by substituting the values ofa_0, a_1 anda_2 into Equation (4.5). Thus:

$F_{MAX} = -1827.4327 + 234.7156D - 5.5244D^2$ (4.48)

The Coefficient of Determination, $r^2 = 0.997$; and $p = 0.000003358$.

For cubic polynomial regression model, Equation (4.9) is applicable.

The applicable normal equations for obtaining estimates of the values of coefficients a_0, a_1, a_2 and a_3 in Equation (4.9) are Equations (4.10a), (4.10b), (4.10c) and (4.10d)

The terms of Equation (4.10a), Equation (4.10b), Equation (4.10c) and Equation (4.10d) for *A. indica* are evaluated as shown in Table 4.36.

Table 4.36: Evaluated Terms for *A. indca*`s Cubic Polynomial Regression of Maximum Uprooting Force (F_{MAX}) on Stem Basal Diameter (D).

Test no	1	2	3	4	5	6	Row sum
F_{MAX} (N)	741	561	525	570	540	195	3132
D(mm)	19.5	19	15.5	17.5	17.3	12	100.8
$F_{MAX}*D$	14450	10659	8138	9975	9342	2340	54903
D^2	380.3	361	240.3	306.3	299.3	144	1731
$F_{MAX}*D^2$	281802.3	202521	126157.5	174591	161622	28080	974773.8

D^3	7414.875	6859	3723.875	5359.375	5177.717	1728	30262.842
$F_{MAX}*D^3$	5494423.375	3847899	1955039.375	3054843.75	2795967.18	336960	17485126.31
D^4	144590.0625	130321	57720.0625	93789.0625	89574.5041	20736	536730.6916
D^5	2819506.219	2476099	894660.9688	1641308.594	1549638.921	248832	9630045.703
D^6	54980371.27	47045881	13867245.02	28722900.39	26808753.33	2985984	174411135

The resulting equations with direct substitution of terms in Table 4.36 into Equation (4.10a), Equation (4.10b), Equation (4.10c) and Equation (4.10d) are:

$3132 = 6a_0 + 100.8a_1 + 1731a_2 + 30262.842a_3$ (4.49a)

$54903 = 100.8a_0 + 17331a_1 + 30262.842a_2 + 536730.6916a_3$ (4.49b)

$974773.8 = 1731a_0 + 30262.842a_1 + 536730.6916a_2 + 9630045.703\, a_3$ (4.49c)

$1148512631 = 30262.842a_0 + 536730.6916a_1 + 9630045.703a_2 + 174411135a_3$ (4.49d)

Solving for the unknown coefficients of Equation (4.49a), Equation (4.49b), Equation (4.49c) and Equation (4.49d), (see matrix A.15 and matrix A.16 in Appendix A), we have:

$a_3 = -0.09286$, $a_2 = 0.05553$, $a_1 = 129.109$, $a_0 = -1194.6837$.

Thus the least square cubic polynomial is:

$F_{MAX} = -1194.6837 + 129.109D + 0.05553D^2 - 0.09286D^3$ (4.50)

The Coefficient of Determination, $r^2 = 0.908$; while $p = 0.002740$.

The summary of the three regression models for *A. indica* species is presented in Table 4.37.

Table 4.37: Results of Regression Analysis of F_{MAX} on D for *A. indica* species

Model	Equation	Coefficient of Determination(r^2)	Probability level (p)
Linear model	$F_{MAX} = 60.85D – 500.22$	0.999	0.00000037
Quadratic model	$F_{MAX} = -1827.4327+234.7156D -5.5244D^2$	0.997	0.000003358
Cubic polynomial model	$F_{MAX} = -1194.6837+129.109D +0.05553D^2-0.09286D^3$	0.908	0.002740

The strength of a relationship is indicated by the Coefficient of Determination (r^2) and the significance expressed by the probability level, p. Comparing the three regression models of Table 4.37, the linear model predicted best relationship between Uprooting force, F_{MAX} and basal diameter (D); for *A. indica* species.

4.2.1.10 Regression Analysis of *M. excelsa*`s Maximum Uprooting Force (F_{Max}) on Stem Basal Diameter (D)

For the regression analysis of *M. excelsa*`s maximum uprooting force (F_{Max}) on stem basal diameter (D), the details of uprooting tests and above ground traits of *M. excelsa* species are shown in Table 4.38.

Table 4.38: Above Ground Traits/Maximum Uprooting Force of *Milicia excelsa* (Juvenile African Teak Tree)

Test No	1	2	3	4	5	6	Mean
Plant Height H(cm)	85.0	70.0	53.0	60.0	50.0	45.0	60.5
Stem Basal Diameter D(mm)	18.5	18.0	11.5	16.5	15.0	10.5	15.0
Maximum Uprooting Force, F_{MAX}(N)	780.0	645.0	501.0	570.0	585.0	246.0	555.0

For the linear regression analysis of *M. excelsa*`s maximum uprooting force (F_{Max}) on stem basal diameter (D), Equation (4.1) is applicable.

The applicable normal equations for obtaining the estimates of the unknowns a_0 and a_1 in Equation (4.1) are Equations (4.2a) and (4.2b). The terms of Equation (4.2a) and Equation (4.2b) for *M. excelsa* are evaluated as shown in Table 4.39.

Table 4.39: Evaluated Terms for Linear Regression of Maximum Uprooting Force on Stem Basal Diameter for *M. excelsa*

Test No	F_{MAX}(N)	D(mm)	$F_{MAX}*D$	D^2 (mm^2)
1	780	18.5	14430	342.3
2	645	18	11610	324
3	501	11.5	5762	132.3
4	570	16.5	9405	272.3
5	585	15	8775	225
6	246	10.5	2583	110.3
Σ	3327	90	52565	1406

The resulting normal equations with direct substitution of terms in Table 4.39 into Equation (4.2a) and Equation (4.2b) are:

$$3327 = 6a_0 + 90a_1 \qquad (4.51a)$$

$$52565 = 90a_0 + 1406a_1 \qquad (4.51b)$$

Solving Equations (4.51a) and (4.51b), and substituting for a_0 and a_1 into Equation (4.1) we obtain:

$$F_{MAX} = -158 + 47.5D \qquad (4.52)$$

The Coefficient of Determination, $r^2 = 0.999$; and $p = 0.00000037$.

Equation 4.52 is the linear regression model of F_{MAX} on D for *M. excelsa* while the graphical illustration of the linear relationship is shown in Figure 4.25.

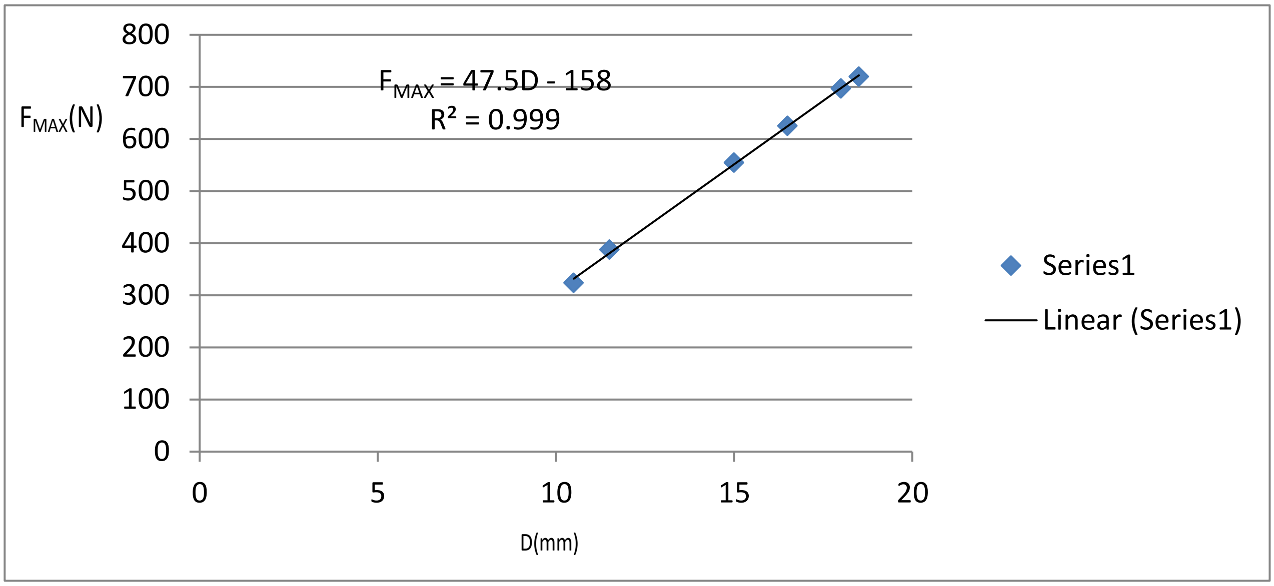

Figure 4.25: Linear regression of F_{MAX} on D for *M. excelsa* species.

For quadratic regression model, Equation (4.5) is applicable. Repeating the procedure outlined for Quadratic regression model in section 4.2.9; after generating similar table to Table 4.35 using the data of Table 4.38 instead of Table 4.33; we obtain that:

$$F_{MAX} = -469.7658 + 92.7066D - 1.5633D^2 \quad (4.53)$$

The Coefficient of Determination, $r^2 = 0.991$; and $p = 0.00002992$.

Equation 4.53 is the quadratic regression model of F_{MAX} on D for *M. excelsa* while the graphical illustration of the quadratic relationship is shown in Figure 4.26.

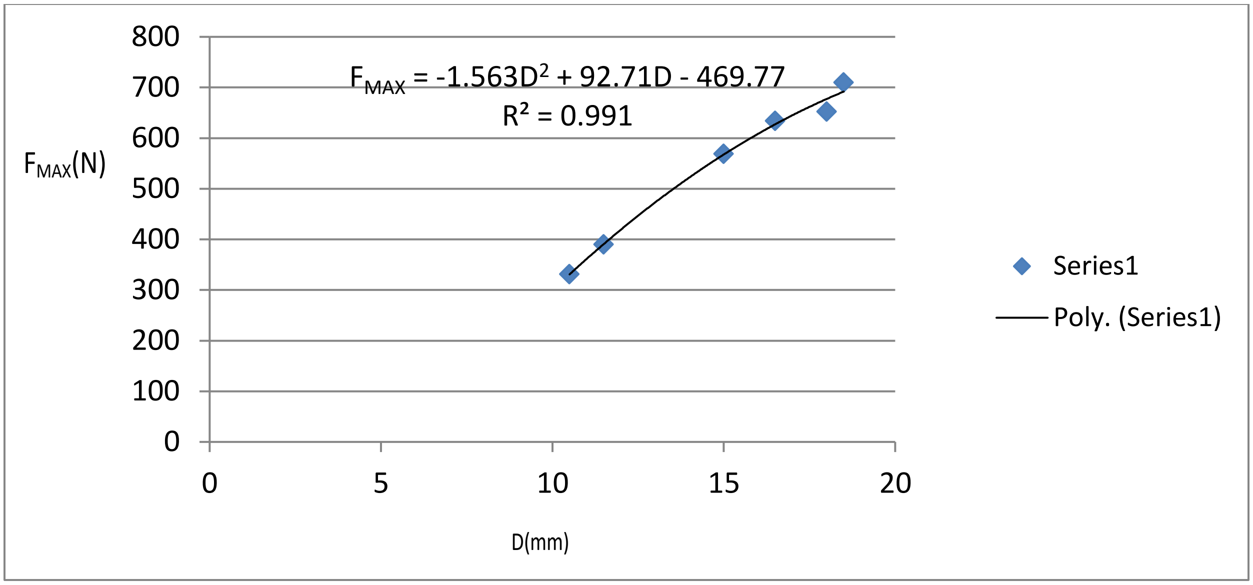

Figure 4.26: Quadratic regression of F_{MAX} on D for *M. excelsa* species.

Going further, for cubic polynomial regression model, Equation (4.9) is applicable. Repeating the procedure outlined for cubic polynomial model in section 4.2.9; after generating similar table to Table 4.36 using the data of Table 4.38 instead of Table 4.33; we obtain that:

$$F_{MAX} = -652.6059 + 131.3977D - 4.2251D^2 + 0.05977D^3 \qquad (4.54)$$

The Coefficient of Determination, $r^2 = 0.990$; and $p = 0.0000369$.

Equation 4.54 is the cubic regression model of F_{MAX} on D for *M. excelsa* while the graphical illustration of the cubic relationship is shown in Figure 4.27.

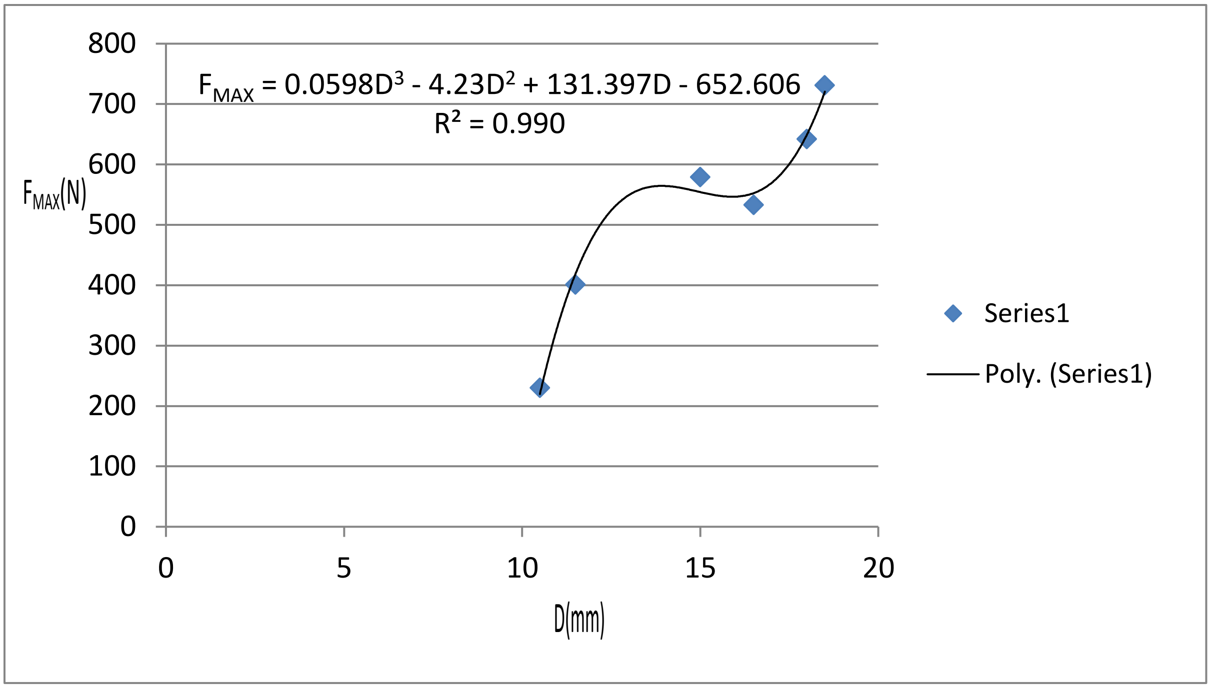

Figure 4.27: Cubic regression of F_{MAX} on D for *M. excelsa* species.

The summary of the three regression models for *M. excelsa* species is presented in Table 4.40.

Table 4.40: Results of Regression Analysis of F_{MAX} on D for *M. excelsa* species

Model	Equation	Coefficient of Determination (r^2)	Probability level (p)
Linear model	F_{MAX} = 47.5D – 158	0.999	0.00000037
Quadratic model	F_{MAX} = -469.7658+92.7066D - 1.5633D^2	0.991	0.00002992
Cubic polynomial model	F_{MAX} = -652.6059+131.3977D +4.2251D^2-0.05977D^3	0.990	0.0000369

The strength of a relationship is indicated by the Coefficient of Determination (r^2) and the significance expressed by the probability level, p. Comparing the three regression models of Table 4.40, the linear model is preferred as having the best relationship between Uprooting force, F_{MAX} and basal diameter (D); for *M. excelsa* species.

4.2.1.11 Regression Analysis of *P. notatum*`s Maximum Uprooting Force (F_{Max}) on Stem Basal Diameter (D)

For the regression analysis of *P. notatum*`s maximum uprooting force (F_{Max}) on stem basal diameter (D), the details of uprooting tests and above ground traits of *P. notatum* species are shown in Table 4.41.

Table 4.41: Above Ground Traits/Maximum Uprooting Force of *Paspalum notatum* (Bahia grass)

Test No	1	2	3	4	5	6	Mean
Plant Height H(cm)	22.0	25.0	34.0	19.0	24.0	19.9	23.98
Stem Basal Diameter D(mm)	6.2	8.0	12.4	4.5	7.3	7.0	7.57
Maximum Uprooting Force, F_{MAX}(N)	43.0	47.5	92.5	49.3	32.5	22.5	47.88

For the linear regression analysis of *P. notatum*`s maximum uprooting force (F_{Max}) on stem basal diameter (D), Equation (4.1) is applicable.

The applicable normal equations for obtaining estimates of the unknowns in Equation (4.1) are Equations (4.2a) and (4.2b). The terms of Equation (4.2a) and Equation (4.2b) for *P. notatum* are evaluated as shown in Table 4.42.

Table 4.42: Evaluated Terms for Linear Regression of Maximum Uprooting Force on Stem Basal Diameter (D) for *P. notatum*

Test No	F_{MAX}(N)	D(mm)	$F_{MAX*}D$	D^2 (mm^2)
1	43	6.2	266.6	38.44
2	47.5	8	380	64
3	92.5	12.4	1147	153.8
4	49.3	4.5	221.9	20.25
5	32.5	7.3	237.3	53.29
6	22.5	7.0	157.5	49
Σ	287.3	45.4	2410	378.7

The resulting normal equations with direct substitution of terms in Table 4.42 into Equation (4.2a) and Equation (4.2b) are:

$287.3 = 6a_0 + 45.4a_1$ (4.55a)

$2410 = 45.4a_0 + 378.7a_1$ (4.55b)

Solving equations (4.55a) and (4.55b), and substituting for a_0 and a_1 into Equation (4.1) we obtain:

$F_{MAX} = - 2.904 + 6.712D$ (4.56)

The Coefficient of Determination, $r^2 = 0.98$; and $p = 0.0001451$.

For quadratic regression model, Equation (4.5) is applicable.

The applicable normal equations for obtaining estimates of a_0, a_1 and a_2 in Equation (4.5) are Equations (4.6a), (4.6b) and (4.6c). The terms of Equation (4.6a), Equation (4.6b) and Equation (4.6c) for *P. notatum* are evaluated as shown in Table 4.43.

Table 4.43: Evaluated Terms for *P. notatum*`s Quadratic Regression of Maximum Uprooting Force (F_{MAX}) on Stem Basal Diameter (D).

Test No	F_{MAX}	D	$F_{MAX}*D$	D^2	$F_{MAX}*D^2$	D^3	D^4
1	43	6.2	266.6	38.44	1652.92	238.328	1477.6336
2	47.5	8	380	64	3040	512	4096
3	92.5	12.4	1147	153.8	14226.5	1906.624	23642.1376
4	49.3	4.5	221.9	20.25	998.325	91.125	410.0625
5	32.5	7.3	237.3	53.29	1731.925	389.017	2839.8241
6	22.5	7.0	157.5	49	1102.5	343	2401
Σ	287.3	45.4	2410	378.7	22752.17	3480.094	34866.6578

The resulting normal equations with direct substitution of terms in Table 4.43 into Equation (4.6a), Equation (4.6b) and Equation (4.6c) are:

$287.3 = 6a_0 + 45.4a_1 + 378.7a_2$ (4.57a)

$2410 = 45.4a_0 + 378.7a_1 + 3480.094a_2$ (4.57b)

$22752.17 = 378.7a_0 + 3480.094a_1 + 34866.6578a_2$ (4.57c)

Solving for the unknown coefficients of Equation (4.57a), Equation (4.57b) and Equation (4.57c), (see matrix A.17 and matrix A.18 in Appendix A), we have:

$a_2 = 2.1941$, $a_1 = -31.6277$, $a_0 = 148.7163$.

Thus the least square quadratic equation is gotten by substituting the values of a_0, a_1 and a_2 into Equation (4.5). Thus:

$F_{MAX} = 148.7163 – 31.6277D + 2.1941D^2$ (4.58)

The Coefficient of Determination, $r^2 = 0.89$; while $p = 0.003812$.

For cubic polynomial regression model, Equation (4.9) is applicable.

The applicable normal equations for obtaining estimates of a_0, a_1, a_2 and a_3 as contained in Equation (4.9) are Equations (4.10a), (4.10b)**,** (4.10c) and (4.10d).

The terms of Equation (4.10a), Equation (4.10b), Equation (4.10c) and Equation (4.10d) for *P. notatum* are evaluated as shown in Table 4.44.

Table 4.44: Evaluated Terms for *P. notatum*`s Cubic Polynomial Regression of Maximum Uprooting Force (F_{MAX}) on Stem Basal Diameter (D).

Test no	1	2	3	4	5	6	Row sum
F_{MAX} (N)	43	47.5	92.5	49.3	32.5	22.5	287.3
D(mm)	6.2	8	12.4	4.5	7.3	7.0	45.4
$F_{MAX}*D$	266.6	380	1147	221.9	237.3	157.5	2410
D^2	38.44	64	153.8	20.25	53.29	49	378.7
$F_{MAX}*D^2$	1652.92	3040	14226.5	998.325	1731.925	1102.5	22752.17
D^3	238.328	512	1906.624	91.125	389.017	343	3480.094

$F_{MAX*}D^3$	10248.104	24320	176362.72	4492.4625	12643.0525	7717.5	235783.839
D^4	1477.6336	4096	23642.1376	410.0625	2839.8241	2401	34866.6578
D^5	9161.3283	32768	293162.5062	1845.2813	20730.7159	16807	374474.8317
D^6	56800.2356	262144	3635215.077	8303.7656	151334.2263	117649	4231446.305

The resulting equations with direct substitution of terms in Table 4.44 into Equation (4.10a), Equation (4.10b), Equation (4.10c) and Equation (4.10d) are:

$287.3 = 6a_0 + 45.4a_1 + 378.7a_2 + 3480.094a_3$ (4.59a)

$2410 = 45.4a_0 + 378.7a_1 + 3480.094a_2 + 34866.6578a_3$ (4.59b)

$22752.17 = 378.7a_0 + 3480.094a_1 + 34866.6578a_2 + 374474.8317 a_3$ (4.59c)

$235783.839=3480.094a_0+34866.6578a_1+374474.8317a_2+4231446.305a_3$(4.59d)

Solving for the unknown coefficients of Equation (4.59a), Equation (4.59b), Equation (4.59c) and Equation (4.59d), (see matrix A.19 and matrix A.20 in Appendix A), we have:

$a_3 = 0.2914$, $a_2 = -5.1947$, $a_1 = 90.3506$, $a_0 = -476.9168$.

Thus the least square cubic polynomial is:

$F_{MAX} = -476.9168+90.3506D -5.1947D^2 +0.2914D^3$ (4.60)

The Coefficient of Determination, $r^2 = 0.83$; while $p = 0.00833$.

The summary of the three regression models for *P. notatum* species is presented in Table 4.45.

Table 4.45: Results of Regression Analysis of F_{MAX} on D for *P. notatum* species

Model	Equation	Coefficient of Determination (r^2)	Probability level (p)
Linear model	$F_{MAX} = 6.712D - 2.904$	0.98	0.0001451
Quadratic model	$F_{MAX} = 148.7163-31.6277D +2.1941D^2$	0.89	0.003812
Cubic polynomial model	$F_{MAX} = -476.9168+90.3506D -5.1947D^2+0.2914D^3$	0.83	0.00833

The strength of a relationship is indicated by the Coefficient of Determination (r^2) and the significance expressed by the probability level, p. Comparing the three regression models of Table 4.45, there is higher linear relationship between Uprooting force, F_{MAX} and basal diameter (D); for *P. notatum* species.

4.2.1.12 Regression Analysis of *C. zizaioides*` Maximum Uprooting Force (F_{Max}) on Stem Basal Diameter (D)

For the regression analysis of *C. zizanioides*`maximum uprooting force (F_{Max}) on stem basal diameter (D), the details of uprooting tests and above ground traits of *C. zizanioides* species are shown in Table 4.46.

Table 4.46: Above Ground Traits/Maximum Uprooting Force of Chrysopogon zizanioides (Vetiver)

Test No	1	2	3	4	5	6	Mean
Plant Height H(cm)	30.0	28.0	25.0	27.5	26.0	15.0	25.5
Stem Basal Diameter D(mm)	13.5	9.0	6.0	6.5	5.0	4.2	7.37
Maximum Uprooting Force, F_{MAX}(N)	35.0	18.4	15.0	18.0	17.0	10.0	18.9

For the linear regression analysis of *C. zizanioides*`maximum uprooting force (F_{Max}) on stem basal diameter (D), Equation (4.1) is applicable.

The applicable normal equations for obtaining estimates of the unknowns in Equation (4.1) are Equations (4.2a) and (4.2b). The terms of Equation (4.2a) and Equation (4.2b) for *C. zizaniodes* are evaluated as shown in Table 4.47.

Table 4.47: Evaluated Terms for Linear Regression of Maximum Uprooting Force on Stem Basal Diameter for *C. zizainoides*

Test No	F_{MAX}(N)	D(mm)	$F_{MAX}*D$	D^2 (mm^2)
1	35	13.5	472.5	182.3
2	18.4	9	165.6	81
3	15	6	90	36
4	18	6.5	117	42.25
5	17	5	85	25
6	10	4.2	42	17.64
Σ	113.4	44.2	972.1	384.1

The resulting normal equations with direct substitution of terms in Table 4.47 into Equation (4.2a) and Equation (4.2b) are:

$113.4 = 6a_0 + 44.2a_1$ (4.61a)

$972.1 = 44.2a_0 + 384.1a_1$ (4.61b)

Solving Equations (4.61a) and (4.61b), and substituting for a_0 and a_1 into Equation (4.1) we obtain:

$F_{MAX} = 1.684 + 2.34D$ (4.62)

The Coefficient of Determination, $r^2 = 0.975$; and $p = 0.0002249$.

Equation 4.62 is the linear regression model of F_{MAX} on D for *C. zizaniodes* while the graphical illustration of the linear relationship is shown in Figure 4.28

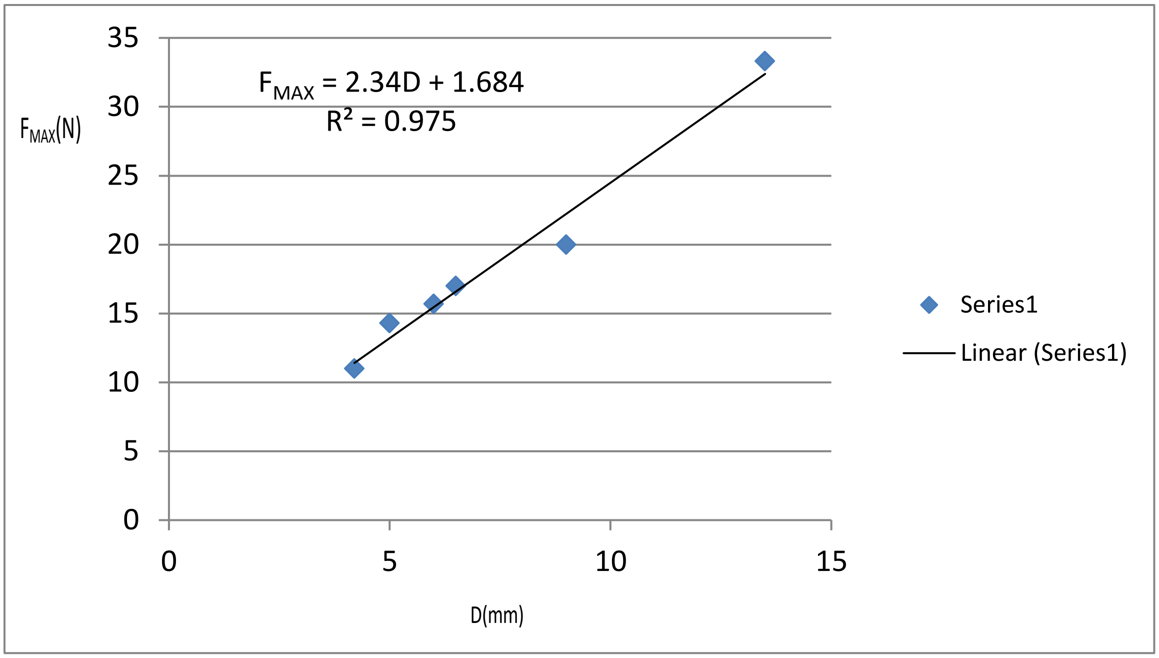

Figure 4.28: Linear regression of F_{MAX} on D for *C. zizaniodes* species.

For quadratic regression model, Equation (4.5) is applicable.

Repeating the procedure outlined for Quadratic regression model in section 4.2.9; after generating similar table to Table 4.35 using the data of Table 4.46 instead of Table 4.33; we obtain that:

$$F_{MAX} = -469.7658 + 92.7066D - 1.5633D^2 \qquad (4.63)$$

The Coefficient of Determination, $r^2 = 0.715$; while $p = 0.020016$.

Equation 4.63 is the quadratic regression model of F_{MAX} on D for *C. zizaniodes* while the graphical illustration of the quadratic relationship is shown in Figure 4.29

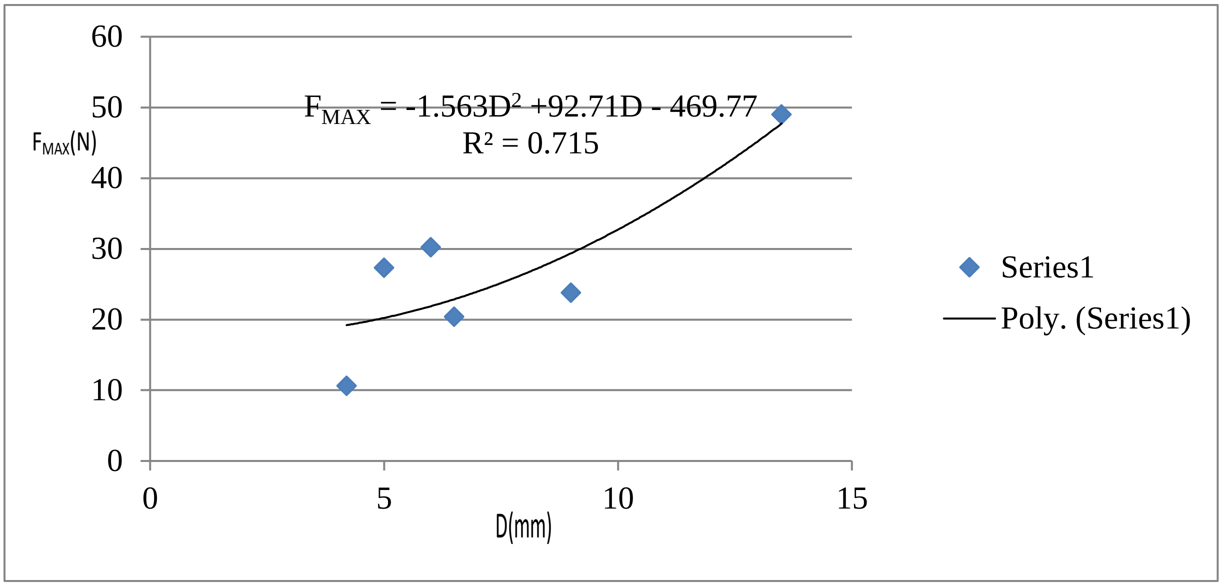

Figure 4.29: Quadratic regression of F_{MAX} on D for *C. zizaniodes* species.

For cubic polynomial regression model, Equation (4.9) is applicable.

Repeating the procedure outlined for cubic polynomial model in section 4.2.9; after generating similar table to Table 4.36 using the data of Table 4.46 instead of Table 4.33; we obtain that:

$$F_{MAX} = -652.6059 + 131.3977D - 4.2251D^2 + 0.05977D^3 \qquad (4.64)$$

The Coefficient of Determination, $r^2 = 0.245$; while $p = 0.0828$.

Equation 4.64 is the cubic regression model of F_{MAX} on D for *C. zizaniodes* while the graphical illustration of the cubic relationship is shown in Figure 4.30.

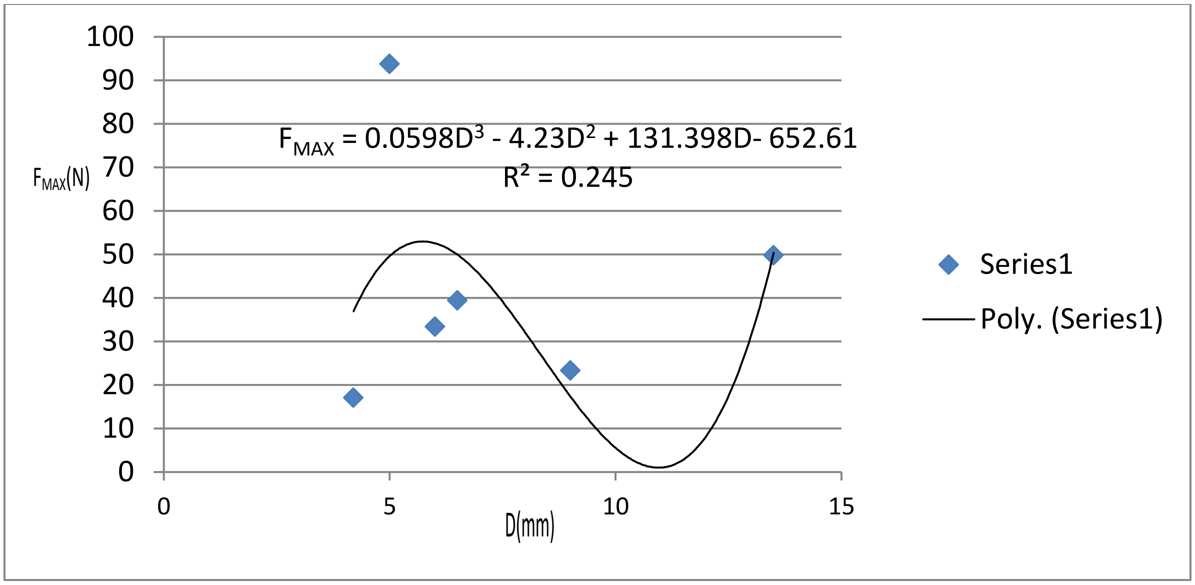

Figure 4.30: Cubic regression of F_{MAX} on D for *C. zizaniodes* species.

The summary of the three regression models for *C. zizaniodes* species is presented in Table 4.48.

Table 4.48: Result of Regression Analysis of F_{MAX} on D for *C. zizzaniodes* species

Model	Equation	Coefficient of Determination (r^2)	Probability level (p)
Linear model	$F_{MAX} = 1.684+2.34D$	0.975	0.0002249
Quadratic model	$F_{MAX} = -469.7658+92.7066D - 1.5633D^2$	0.715	0.020016
Cubic polynomial model	$F_{MAX} = -652.6059+131.3977D - 4.2251D^2+0.05977D^3$	0.245	0.0828

Comparing the three regression models of Table 4.48, there is higher linear relationship between Uprooting force, F_{MAX} and basal diameter (D); for *C. zizaniodes* species.

The summary of the regression models that best describes the relationship between maximum uprooting force (F_{MAX}) and stem basal diameter (D) for the twelve plant species studied is presented in Table 4.49.

Table 4.49: Appropriate regression models of F_{MAX} on D for the twelve species studied.

Species	Best model	Equation	Coefficient of Determination (r^2)	Probability level (p)
O. abyssinica	Linear model	$F_{MAX} = 46D – 117.22$	0.999	0.00000037
C. sinensis	Linear model	$F_{MAX} = 156D – 1790.94$	0.999	0.00000037
V. amygdalina	Linear model	$F_{MAX} = 43.2D – 48.067$	0.999	0.00000037
C. dactylon	Linear model	$F_{MAX} = 5.121D – 2.215$	0.997	0.00000336
P. purpureum	Linear model	$F_{MAX} = 25.32D –128.54$	0.996	0.00000596
S. officinarium	Linear model	$F_{MAX} = 15.057D – 31.41$	0.90	0.003197
M. indica	Linear model	$F_{MAX} = 50.199D – 350.88$	0.998	0.0000015
A. occidentale	Linear model	$F_{MAX} = 69.8D – 590.493$	0.999	0.00000037
A indica	Linear model	$F_{MAX} = 60.85D – 500.22$	0.999	0.00000037
M. excelsa	Linear model	$F_{MAX} = 47.5D – 158$	0.999	0.00000037
P. notatum	Linear model	$F_{MAX} = 6.712D – 2.904$	0.98	0.00014513
C. zizaniodes	Linear model	$F_{MAX} = 1.684+2.34D$	0.975	0.0002249

From Table 4.49, the values of coefficient of Determination (r^2) show that maximum uprooting force (F_{MAX}) is positively correlated with the plants basal diameter (D). The relationships between the plants maximum uprooting force (F_{MAX}) and the basal diameter (D), expressed in Table 4.49 are all linear and significant at 95% confidence level as confirmed by the various values of p ($P< 0.05$).

4.2.2 Analysis of Variance (ANOVA) to Test for Differences between Species in Uprooting Resistance

The method of analysis of variance serves here a useful purpose in performing the test of significance on difference between species in terms of their uprooting resistances as shown in Table 4.50. The uprooting resistances of the six samples of the twelve species under study are computed by dividing each uprooting force (F_{MAX}) by the respective basal area ($\Pi D^2/4$).

Null and Alternative Hypothesis:

H_0: all $t_i = 0$; there is no significant difference in the uprooting resistance between species.

H_1: all $t_i \neq 0$; there is significant difference in the uprooting resistance between species.

Where t_i is the difference between species in Uprooting resistance

Table 4.50: ANOVA to Test for Differences between Species in Uprooting Resistance (N/mm^2)

Plant species	Uprooting resistance for each species sample, σ_{MAX} (N/mm^2)						Row Average	Sum of row square
	1	2	3	4	5	6		
O. abyssinica	3.10	1.11	2.93	4.05	4.59	4.93	3.45	81.2025
C. sinensis	3.70	3.35	3.60	1.53	1.36	1.36	2.48	43.9126
V. amygdalina	3.06	2.66	3.91	3.82	3.30	2.79	3.26	64.9938
C. dactylon	1.63	0.86	1.67	1.35	1.75	2.34	1.60	16.5460
P. purpureum	1.69	1.00	1.10	1.02	0.97	0.98	1.13	8.0078
S.officinarium	0.95	1.20	1.21	1.14	2.10	1.10	1.28	10.7262
M. indica.	3.08	1.73	1.73	1.68	2.94	2.08	2.21	31.2646
A. occidentale	2.52	2.46	1.31	3.36	2.05	2.13	2.305	34.1471
A. indica.	2.48	1.98	2.78	2.37	2.30	1.72	2.27	31.6645
M. excelsa.	2.90	2.53	4.82	2.61	3.31	2.84	3.18	63.8771
P. notatum	1.42	0.94	0.77	3.1	0.78	0.58	1.265	14.0477
C. zizanioides	0.24	0.29	0.53	0.54	0.87	0.72	0.53	1.9895
Column Total	26.77	26.36	26.3	26.7	26.3	23.54	24.96	402.379
Column Average	2.23	1.68	2.20	2.21	2.19	1.96	2.08	33.5316

The overall mean of uprooting resistance: $\bar{\sigma}_{MAX} = \sum_{i=1}^{P}(\bar{\sigma}_i)/P$

$\bar{\sigma}_{MAX}$ = (3.45+2.48+3.26+1.6+1.13+1.28+2.21+2.305+2.27+3.18+1.265+0.53)/12

= 24.96/12 = 2.08 N/mm^2.

Correction factor = $P_* n (\bar{\sigma}_{MAX})^2 = 12 \times 6 \times 2.08^2 = 311.5008$

Sum of squares of the 72 data set, $\sum(\bar{\sigma}_{ij})^2 = 402.3794$

$n_* \sum_{i=1}^{P}(\bar{\sigma}_i)^2 = 6(3.45^2+2.48^2+3.26^2+1.6^2+1.13^2+1.28^2+2.2^2+2.305^2+2.27^2+3.18^2+1.265^2$

$+0.53^2) = 6(61.499335) = 368.9961$.

Total variation = 402.3794 - 311.5008 = 90.8786

Species variation = 368.9961- 311.5008 = 57.4953.

Residual variation (within Species) = 90.8786 - 57.4953 = 33.3833.

Table 4.51: ANOVA Result of uprooting resistance for the twelve species

Source of variation	Sum of squares	Degree of freedom	Mean square	F-Value
Between species	57.4953	11	5.2268	9.394
Within species	33.3833	60	0.5564	
Total	90.8786	71		

F-value as computed in Table 4.51 is 9.394. F-critical from upper percentage points of F-Distribution; $F_{0.05,11,60}$, is 1.96. By comparison, F-value is greater $F_{0.05,11,60}$, (F-value > F-critical) which confirms that there is significant difference in the uprooting resistance between species. In other words we reject the null hypothesis.

4.2.3 Duncan Multiple Range Test

Duncan's multiple range tests is employed as a general class of multiple comparison procedure. In performing the test, the means of the uprooting resistance of the six samples of the twelve species were ranked starting from the largest to the smallest as shown in Table 4.52.

Table 4.52: Duncan Multiple Range Test

Species	Rank	$\bar{\sigma}_{MAXi}$	$(\bar{\sigma}_{MAXi} - \bar{\sigma}_{MAX})^2$
O. abyssinica	1	3.45	1.8769
V. amygdalina	2	3.26	1.3924
M. excelsa	3	3.18	1.2100
C.sinensis	4	2.48	0.1600
A. occidentale	5	2.31	0.0529
A. indica	6	2.27	0.0361
M. indica	7	2.21	0.0169
C. dactylon	8	1.60	0.2304
S.officinarium	9	1.28	0.6400
P. notatum	10	1.27	0.6561
P. purpureum	11	1.13	0.9025
C. zizanioides	12	0.53	2.4025
Summation		24.97	9.5767

$\bar{\sigma}_{MAXi}$ = Mean of Uprooting resistance for each species;

$\bar{\sigma}_{MAX}$ = Overall mean of Uprooting resistance = 24.97/12 = 2.08.

The combined variance of uprooting resistance, $S^2/P = \Sigma(\bar{\sigma}_{MAXi} - \bar{\sigma}_{MAX})^2/P$ (4.65)

(Where S^2 denotes variance in each species and P denotes number of species)

$S^2/p = 9.5767/12 = 0.7981$.

Standard Error, $SE = (S^2/(n*P))^{0.5}$ (n = number of trials = 6).

$= (9.5767/(6*12))^{0.5} = 0.3647$.

Shortest significant range; $R_p = \Upsilon_{\alpha}(p,df)_{*}SE$;

Where Υ_{α} denotes significant result level ($\alpha = 0.05$).

p denotes means number in the subset (Ranging from 2 to 12);

df denotes degree of freedom;

$R_2 = \Upsilon_{0.05}(2,60)xSE = 2.83 \text{ x } 0.3647 = 1.0321$;

$R_3 = \Upsilon_{0.05}(3,60)xSE = 3.4 \text{ x } 0.3647 = 1.240$;

$R_4 = \Upsilon_{0.05}(4,60)xSE = 3.74 \text{ x } 0.3647 = 1.3640$;

$R_5 = \Upsilon_{0.05}(5,60)xSE = 3.98 \text{ x } 0.3647 = 1.4515$;

$R_6 = \Upsilon_{0.05}(6,60)xSE = 4.16 \text{ x } 0.3647 = 1.5172$;

$R_7 = \Upsilon_{0.05}(7,60)xSE = 4.31 \text{ x } 0.3647 = 1.5719$;

$R_8 = \Upsilon_{0.05}(8,60)xSE = 4.44 \text{ x } 0.3647 = 1.6193$;

$R_9 = \Upsilon_{0.05}(9,60)xSE = 4.55 \text{ x } 0.3647 = 1.6594$;

$R_{10} = \Upsilon_{0.05}(10,60)xSE = 4.65 \text{ x } 0.3647 = 1.6959$;

$R_{11} = \Upsilon_{0.05}(11,60)xSE = 4.73 \text{ x } 0.3647 = 1.7250$;

$R_{12} = \Upsilon_{0.05}(12,60)xSE = 4.81 \text{ x } 0.3647 = 1.7542$.

The pair wise comparison of means (the largest minus the smallest, the largest minus the second smallest, up to the largest minus the second largest, then the second largest minus the smallest, the second largest minus the second smallest, and so on, finishing with the second smallest minus the smallest. Thus we have Table 4.53.

Table 4.53: Multiple Range Test Pair Wise Comparison of Mean

Ranked species compared (1)	Differences between species mean uprooting resistances. (2)	Shortest significant range (3)	Column (2) minus Column(3) (4)	Significant or No significant difference (5)
1,12	3.45 – 0.53 =2.93	R_{12} = 1.7542	1.1758	significant
1,11	3.45 – 1.13 = 2.32	R_{11} = 1.7250	0.595	significant
1,10	3.45 – 1.27 = 2.18	R_{10} = 1.6959	0.4841	significant
1,9	3.45 – 1.28 = 2.17	R_9 = 1.6594	0.5106	significant
1,8	3.45 – 1.60 = 1.85	R_8 = 1.6193	0.2307	significant
1,7	3.45 – 2.21 = 1.24	R_7 = 1.5719	- 0.3319	Not significant
1,6	3.45 – 2.27 = 1.18	R_6 = 1.5172	- 0.3372	Not significant
1,5	3.45 – 2.31 = 1.14	R_5 = 1.4515	- 0.3115	Not significant
1,4	3.45 – 2.48 = 0.97	R_4 = 1.3640	- 0.394	Not significant
1,3	3.45 – 3.18 = 0.27	R_3 = 1.240	- 0.97	Not significant
1,2	3.45 – 3.26 = 0.19	R_2 = 1.0321	- 0.8421	Not significant
2,12	3.26 – 0.53 = 2.73	R_{11} = 1.7250	1.005	significant
2,11	3.26 – 1.13 = 2.13	R_{10} = 1.6959	0.4341	significant
2,10	3.26 – 1.27 = 1.99	R_9 = 1.6594	0.3306	significant
2,9	3.26 – 1.28 = 1.98	R_8 = 1.6193	0.3607	significant
2,8	3.26 – 1.60 = 1.66	R_7 = 1.5719	0.0881	significant
2,7	3.26 – 2.21= 1.05	R_6 = 1.5172	- 0.4672	Not significant
2,6	3.26 – 2.27 = 0.99	R_5 = 1.4515	- 0.4615	Not significant
2,5	3.26 – 2.31= 0.95	R_4 = 1.3640	- 0.414	Not significant
2,4	3.26 – 2.48 = 0.78	R_3 = 1.240	- 0.46	Not significant
2,3	3.26 – 3.18 = 0.08	R_2 = 1.0321	- 0.9521	Not significant
3,12	3.18 – 0.53 = 2.65	R_{10} = 1.6959	0.9541	significant
3,11	3.18 – 1.13 = 2.05	R_9 = 1.6594	0.3906	significant
3,10	3.18 – 1.27 = 1.91	R_8 = 1.6193	0.2907	significant
3,9	3.18 – 1.28 = 1.90	R_7 = 1.5719	0.3281	significant
3,8	3.18 – 1.60 = 1.58	R_6 = 1.5172	0.0628	significant

Table 4.53: Multiple Range Test Pair wise Comparison of Means (CONT.)				
(1)	(2)	(3)	(4)	(5)
3,7	3.18 – 2.21 = 0.97	R_5 = 1.4515	- 0.4815	Not significant
3,6	3.18 – 2.27 = 0.91	R_4 = 1.3640	- 0.454	Not significant
3,5	3.18 – 2.31 = 0.87	R_3 = 1.240	- 0.37	Not significant
3,4	3.18 – 2.48 = 0.70	R_2 = 1.0321	-0.3321	Not significant
8,12	1.60 – 0.53 = 1.07	R_5 = 1.4515	- 0.3815	Not significant
8,11	1.60 – 1.13 = 0.47	R_4 = 1.3640	- 0.894	Not significant
8,10	1.60 – 1.27 = 0.33	R_3 = 1.240	- 0.91	Not significant
8,9	1.60 – 1.28 = 0.32	R_2 = 1.0321	- 0.7121	Not significant
9,12	1.28 – 0.53 = 0.75	R_4 = 1.3640	- 0.614	Not significant
9,11	1.28 – 1.13 = 0.15	R_3 = 1.240	- 1.090	Not significant
9,10	1.28 – 1.27 = 0.01	R_2 = 1.0321	- 1.0221	Not significant
10,12	1.27 – 0.53 = 0.74	R_3 = 1.240	- 0.500	Not significant
10,11	1.27 – 1.13 = 0.14	R_2 = 1.0321	- 0.8921	Not significant
11,12	1.13 – 0.53 = 0.600	R_2 = 1.0321	-0.4321	Not significant

The means that are not significantly different are said to be of the same resistance group. Consequently, based on this comparison (Duncan's multiple range test) species are classified into two resistance groups:

- Group 1: *O. abyssinica, V. amygdalina, M. excelsa, C. sinensis, A. occidentale, A. indica, and M. indica.*
- Group 2: *C. dactylon, S. officinarium, P. notatum, P. purpureum and C. zizanioides.*

4.2.4 Discriminant Analysis on the Morphological Traits of the Twelve Species

The major application of Discriminant Analysis as statistical technique here is to distinguish between sets of morphological traits based on their contribution to the uprooting resistance of the plant species being tested. The morphological traits under consideration here are; Plant Slenderness Ratio(H/D), Root slenderness ratio (LR_1/D);Root relative volume(V/D); Relative root dry weight(DWR/D); Percentage tap root dry weight(%DWR_1); Specific root length(SRL);Percentage fine roots < 0.5mm.(%FR<0.5mm).

4.2.4.1 Analysis of Variance on Plant Slenderness Ratio (H/D) of the twelve species.

The plant slenderness ratio (H/D) is the inter-specific allometry of maximum plant height (H_{MAX}) with respect to the basal diameter (D). The slenderness ratio of the six sample juvenile plants of the twelve species under study were computed and recorded as shown in Table 4.54.

Table 4.54: ANOVA on Plant Slenderness Ratio (H/D) of the twelve Species

Plant species	H/D (cm/cm)						Row Total	Row Average	Variance	Sum of row square
	1	2	3	4	5	6				
O. abyssinica	47.22	31.94	47.4	52.76	50.96	53	283.28	47.21	311.599	13686.2
V. amygdalina	33.95	29.24	33.6	37.67	45.87	30.59	210.92	35.15	180.833	7595.37
M. excelsa	45.95	38.89	46.09	36.36	33.33	42.86	243.48	40.58	137.622	10018
C. sinensis	41.57	40.74	45.77	24.57	26.25	27.93	206.83	34.47	425.763	7555.54
A. occidentale	28.46	34.78	33.95	41.67	29.09	30.8	198.75	33.13	119.887	6703.48
A. indica	35.13	31.58	22.58	23.14	34.68	22.08	169.19	28.2	196.081	4966.96
M. indica	47.04	27.59	35.71	34.29	34.57	29.23	208.43	34.74	233.946	7474.46
C. dactylon	43.75	42.3	36.92	36.67	47	43.02	249.66	41.61	82.123	10470.9

S. officinarium	48.39	43.48	45	52	45.75	49.11	283.73	47.29	48.838	13466
P. notatum	35.48	31.25	27.42	42.22	32.88	28.43	197.68	32.95	146.2	6659.14
P. purpureum	49.17	31.67	35.71	33.08	41.47	32.31	223.41	37.24	235.195	8553.87
C. zizaniodes	22.22	31.11	41.67	42.31	52	35.71	225.02	37.5	528.3	8967.29

Over all Mean of the slenderness ratio (H/D) = (47.21+35.15+40.58+34.47+33.13+ 28.2+ 34.74 +41.61+47.29+32.95+37.24+37.5)/12 = 37.51.

Sum of squares of the 72 data set = 138,054.1342.

n = number of samples = 6;

$\overline{x}_i$ = Respective means of Slenderness ratio of the twelve species.

$n\Sigma\overline{x}_i^2 = 6(47.21^2+35.5^2+40.58^2+34.47^2+33.13^2+28.2^2+34.74^2+41.61^2+47.29^2+ 32.95^2+37.24^2+37.5^2) = 103620.9732$

Correction factor = $(12x6)x(37.51)^2$ = 101,304.0072.

Total variation = 138,054.1342- 101,304.0072 = 36750.127.

Species variation = 103620.9732 - 101,304.0072 = 2316.966

Residual variation (within species) = 36750.127- 2316.966 = 34433.161.

Table 4.55: ANOVA Result of Plant Slenderness Ratio (H/D)

Source of variation	Sum of squares	Degree of freedom	Mean square	F- Value
Between species	2316.966	11	210.6333	
Within species	34433.161	60	573.8860	0.367
Total	36750.127	71		

From Table 4.55, F-value of plant slenderness ratio is 0.367.From upper percentage points of F-Distribution, $F_{0.05,11,60}$ = 1.96. By comparison F-value is less than $F_{0.05,11,60}$, which shows that there is no significant difference in plant slenderness ratio for the twelve species. In other words, the plant slenderness ratio plays small or no significant role in the observed difference in the uprooting resistance of the twelve species.

4.2.4.2 Analysis of Variance (ANOVA) on Root Slenderness Ratio (LR_1/D) of the twelve species.

The root slenderness ratio (LR_1/D) is a morphological trait measured as the ratio of the tap root length (LR1) to the basal diameter of the plant (D). The root slenderness ratio for the six tested samples of the twelve species is shown in Table 4.56.

Table 4.56**:** ANOVA on Root Slenderness Ratio (LR_1/D)

plant Species	LR_1/D (cm/cm)						Row total	Row average	Sum of row square
	1	2	3	4	5	6			
O. abyssinica	26.42	22.75	28.18	21.18	15.27	14.68	128.58	21.43	2911.205
V. amygdalina	72.85	76.90	56.21	65.65	80.49	76.90	429.0	71.50	31082.47
M. excelsa	88.80	86.40	55.20	79.20	72.00	50.40	432.0	72.0	32394.24
C. sinensis	42.04	35.69	37.54	33.58	35.96	38.39	223.2	37.2	8344.919
A. occidentale	48.85	45.67	64.34	71.49	43.69	44.56	318.6	53.1	17616.94
A. indica	53.16	51.8	42.26	47.71	47.16	32.71	274.8	45.8	12865.39
M. indica	56.72	44.22	55.50	53.36	32.02	39.58	281.4	46.9	13691.96
C. dactylon	22.60	36.73	22.04	25.43	11.30	12.10	130.2	21.7	3266.399
S. officinarium	41.80	31.01	26.97	33.71	28.59	45.52	207.6	34.6	7462.064
P. notatum	19.66	25.36	39.31	14.27	23.14	22.26	144.0	24.0	3809.521
P. purpureum	28.93	24.11	28.13	26.12	27.32	26.19	160.8	26.8	4324.087
C. zizaniodes	41.21	27.48	18.32	19.84	15.26	12.89	135.0	22.5	3581.682

Over all total of Root Slenderness Ratio for the twelve species = (128.58+429.0+432.0+ 223.2+318.6+274.8+281.4+130.2 +207.6 +144.0+160.8+135.0) = 2865.18.

Over all mean of root slenderness ratio = 2865.18/ (12x6) = 39.79.

Sum of squares of the 72 data set = 141,350.874.

$n\Sigma x_i^2 = 6(21.43^2+71.5^2+72.0^2+37.2^2+53.1^2 +45.8^2+46.9^2+21.7^2 +34.6^2+24.0^2 +26.8^2+ 22.5^2)$ =136348.4094.

Correction factor =$12x6x39.79^2$ = 113993.5752.

Total variation = 141,350.874- 113993.5752= 27357.2988.

Species variation = 136348.4094 - 113993.5752 = 22354.8342

Residual variation (within species) = 27357.2988 - 22354.8342 = 5002.4646

Table4. 57: ANOVA Result of Root Slenderness Ratio (LR_1/D)

Source of variation	Sum of squares	Degree of freedom	Mean square	F- Value
Between species	22354.8342	11	2032.2577	24.375
Residual (Within species)	5002.4646	60	83.3744	
Total	27357.2988	71		

From Table 4.57, F-value of root slenderness ratio is 24.375. From upper percentage points of F-Distribution, $F_{0.05,11,60}$ = 1.96. By comparison F-value for root slenderness ratio is greater than $F_{0.05,11,60}$, which shows that there is significant difference in root slenderness ratio for the twelve species. In other words, the root slenderness ratio has played a significant role in the observed difference in the uprooting resistance of the twelve species.

4.2.4.3 Analysis of Variance (ANOVA) on Relative Root Volume (V/D) of the twelve species.

The Relative root volume (V/D) is a morphological trait measured as the ratio of the volume of the plant root (V) to the plant`s basal diameter (D). The Relative root volume (V/D) of the six tested samples of the twelve species is shown in Table 4.58.

Table 4.58: ANOVA on Relative Root Volume (V/D)

Plant Species	V/D (cm^3/cm)						Row total	Row average	Row square sum
	1	2	3	4	5	6			
O. abyssinica	0.76	0.66	0.82	0.62	0.44	0.42	3.72	0.62	2.44
V. amygdalina	0.51	0.54	0.39	0.40	0.56	0.60	3.00	0.50	1.5374
M. excelsa	0.27	0.26	0.17	0.24	0.22	0.16	1.32	0.22	0.301
C. sinensis	0.27	0.23	0.24	0.22	0.23	0.25	1.44	0.24	0.3472
A. occidentale	0.30	0.28	0.40	0.44	0.27	0.29	1.98	0.33	0.679
A. indica	0.21	0.20	0.17	0.19	0.19	0.12	1.08	0.18	0.1996
M. indica	0.41	0.32	0.40	0.39	0.23	0.29	2.04	0.34	0.7196
C. dactylon	0.25	0.41	0.24	0.28	0.13	0.13	1.44	0.24	0.4004
S. officinarium	0.14	0.10	0.09	0.11	0.09	0.13	0.66	0.11	0.0748
P. notatum	0.16	0.21	0.33	0.12	0.19	0.19	1.20	0.20	0.2652
P. purpureum	0.32	0.27	0.31	0.29	0.31	0.30	1.80	0.30	0.5416
C. zizaniodes	0.20	0.13	0.09	0.10	0.07	0.07	0.66	0.11	0.0848

Over all total of Relative root volume (V/D) = 3.72+3.0+1.32+1.44+ 1.98+1.08 +2.04 +1.44+0.66+1.2+1.8+0.66 = 20.34.

Over all mean of Relative root volume = 20.34/(12x6) = 0.2825.

Sum of squares of the 72 data = 7.5906.

$n\Sigma x_i^2 = 6(0.62^2+0.5^2+0.22^2+0.24^2+0.33^2 +0.18^2+0.34^2+0.24^2+0.11^2+0.2^2+0.3^2+0.11^2)$

$= 7.2546.$

Correction factor = $20.34^2/(12x6) = 5.7461$.

Total variation = 7.5906 - 5.7461 = 1.8445.

Species variation = 7.2546 - 5.7461= 1.5085

Residual variation (within species) = 1.8445 - 1.5085 = 0.336

Table4.59: ANOVA Result of Relative Root Volume (V/D)

Source of variation	Sum of squares	Degree of freedom	Mean square	F- value
Between species	1.5085	11	0.1371	24.482
Residual (Within species)	0.336	60	0.0056	
TOTAL	1.8445	71		

From Table 4.59, F-value of root slenderness ratio is 24.482. From upper percentage points of F-Distribution, $F_{0.05,11,60}$ = 1.96. By comparison F-value for relative root volume is greater than $F_{0.05,11,60}$, which shows that there is significant difference in root slenderness ratio for the twelve species. In other words, the relative root volume has played a significant role in the observed difference in the uprooting resistance of the twelve species.

4.2.4.4 Analysis of Variance on Relative Root Dry Weight (DWR/D) of all the species.

The Relative root dry weight (DWR/D) is a morphological trait measured as the ratio of the weight of dry root tissue (DWR) to the plant basal diameter (D). The Relative root dry weight of the six tested samples of the twelve species is shown in Table 4.60.

Table4.60: ANOVA on Relative Root Dry Weight (DWR/D)

Plant Species	DWR/D (g/cm)						Row total	Row average	Sum of Row square
	1	2	3	4	5	6			
O. abyssinica	0.44	0.38	0.47	0.36	0.26	0.25	2.16	0.36	0.8186
V. amygdalina	0.29	0.30	0.22	0.26	0.32	0.29	1.68	0.28	0.4766
M. excelsa	0.14	0.13	0.08	0.12	0.11	0.08	0.66	0.11	0.0819
C. sinensis	0.16	0.13	0.14	0.13	0.14	0.14	0.84	0.14	0.1182
A. occidentale	0.12	0.11	0.16	0.18	0.11	0.10	0.78	0.13	0.1066
A. indica	0.16	0.16	0.13	0.15	0.14	0.10	0.84	0.14	0.1202
M. indica	0.31	0.25	0.31	0.30	0.18	0.21	1.56	0.26	0.4212
C. dactylon	0.08	0.14	0.08	0.09	0.04	0.05	0.48	0.08	0.0446
S. officinarium	0.07	0.05	0.05	0.06	0.05	0.08	0.36	0.06	0.0224
P. notatum	0.06	0.07	0.11	0.04	0.07	0.07	0.42	0.07	0.032
P. purpureum	0.11	0.09	0.10	0.10	0.10	0.10	0.60	0.10	0.0602
C. zizaniodes	0.07	0.05	0.03	0.04	0.03	0.02	0.24	0.04	0.0112

Over all total of Relative root dry weight (DWR/D) of the tested samples of all the species = 2.16+1.68+0.66+0.84+0.78+0.84+1.56+0.48+0.36+0.42+0.60+0.24 = 10.62.

Over all mean of Relative root dry weight = 10.62/ (12x6) = 0.1475.

Sum of squares of the 72 data = 2.3138; Correction factor = 10.62^2/ (12x6) = 1.56645.

$n\Sigma x_i^2 = 6(0.36^2+0.28^2+0.11^2+0.14^2+0.13^2+0.14^2+0.26^2+0.08^2+0.06^2+0.07^2+0.10^2+0.04^2) = 2.2218$.

Total variation = 2.3138 - 1.56645 = 0.74735.

Species variation = 2.2218 -1.56645 = 0.6554.

Residual variation (within species) = 0.7474–0.6554 = 0.092.

Table 4.61: ANOVA on Relative Root Dry Weight (DWR/D)

Source of variation	Sum of squares	Degree of freedom	Mean square	F- value
Between species	0.6554	11	0.05958	38.941
Residual (Within species)	0.092	60	0.00153	
Total	0.7474	71	*********	

From Table 4.61, F-value of relative root dry weight is 38.941. From upper percentage points of F-Distribution, $F_{0.05,11,60}$ = 1.96. By comparison F-value for relative root dry weight is greater than $F_{0.05,11,60}$, which shows that there is significant difference in relative root dry weight for the twelve species. In other words, the relative root dry weight has played a significant role in the observed difference in the uprooting resistance of the twelve species.

4.2.4.5 **Analysis of Variance** on **Percentage Tap Root Dry Weight (%DWR_1) of the twelve species.**

The Percentage Dry Weight of Tap Root (%DWR_1) is measured as the ratio of the dry weight of tap root (DWR_1) to the total dry weight of root tissue (DWR). The percentage dry weight of tap root of the six tested samples of the twelve species is shown in Table 4.62.

Table4.62: ANOVA on Percentage Dry Weight of Tap Root (%DWR_1)

Plant Species	%DWR_1						Row total	Row average	Sum of Row square
	1	2	3	4	5	6			
O. abyssinica	0.18	0.16	0.20	0.15	0.11	0.10	0.90	0.15	0.1426
V. amygdalina	0.51	0.54	0.39	0.46	0.56	0.54	3.00	0.50	1.5206
M. excelsa	0.84	0.82	0.52	0.75	0.68	0.47	4.08	0.68	2.8942
C. sinensis	0.49	0.41	0.43	0.39	0.42	0.44	2.58	0.43	1.1152
A. occidentale	0.69	0.39	0.55	0.61	0.37	0.9	2.70	0.45	1.4478
A. indica	0.44	0.43	0.35	0.40	0.39	0.27	2.28	0.38	0.8860
M. indica	0.30	0.24	0.30	0.28	0.17	0.21	1.50	0.25	0.3890
C. dactylon	0.25	0.41	0.24	0.28	0.13	0.13	1.44	0.24	0.4004
S. officinarium	0.30	0.22	0.19	0.24	0.21	0.34	1.50	0.25	0.3918
P. notatum	0.18	0.23	0.36	0.13	0.21	0.21	1.32	0.22	0.3200
P. purpureum	0.22	0.18	0.21	0.19	0.20	0.20	1.20	0.20	0.2410
C. zizaniodes	0.33	0.22	0.15	0.16	0.12	0.10	1.08	0.18	0.2298

Over all total of Percentage Tap Root Dry Weight (%DWR_1) of the tested samples of all the species = 0.90+3.0+4.08+2.58+2.7+2.28+1.5+1.44+1.5+1.32+1.20+1.08 = 23.58.

Over all mean of Percentage tap root dry weight = 23.58/ (12x6) = 0.3275.

Sum of squares of the 72 data = 9.9784.

Correction factor = 23.58^2/ (12x6) = 7.7225.

$n\Sigma x_i^2 = 6(0.15^2+0.5^2+0.68^2+0.43^2+0.45^2+0.38^2 +0.25^2 +0.24^2+0.25^2+0.22^2+0.20^2+0.18^2)$

= 9.4206.

Total variation = 9.9784 - 7.7225 = 2.2559.

Species variation = 9.4206- 7.7225 = 1.6981

Residual variation (within species) = 2.2559 – 1.6981= 0.5578.

Table4.63: ANOVA Results of Percentage Tap Root Dry Weight (%DWR_1)

Source of variation	Sum of squares	Degree of freedom	Mean square	F- value
Between species	1.6981	11	0.1544	16.608
Residual(Within species)	0.5578	60	0.009297	
Total	2.2559	71		

From Table 4.63, F-value of Percentage Tap Root Dry Weight is 38.941. From upper percentage points of F-Distribution, $F_{0.05,11,60}$ = 1.96. By comparison F-value for Percentage Tap Root Dry Weight is greater than $F_{0.05,11,60}$, which shows that there is significant difference in Percentage tap root dry weight for the twelve species. In other words, the Percentage Tap Root Dry Weight has played a significant role in the observed difference in the uprooting resistance of the twelve species.

4.2.4.6 Analysis of Variance on Root Density (RTD) of the twelve species.

The Root Density (RTD) is measured as the ratio of the total root dry weight (DWR) to the total root volume (V). The Root Density (RTD) of the six tested samples of the twelve species is shown in Table 4.64.

Table 4.64: ANOVA on Root Density (RTD) (g/cm^3)

Plant Species	RTD (g/cm^3)						Row total	Row average	Sum of Row square
	1	2	3	4	5	6			
O. abyssinica	0.72	0.62	0.76	0.58	0.41	0.39	3.48	0.58	2.137
V. amygdalina	0.57	0.60	0.44	0.51	0.63	0.61	3.36	0.56	1.9076
M. excelsa	0.62	0.60	0.38	0.55	0.50	0.35	3.00	0.50	1.5638
C. sinensis	0.66	0.56	0.59	0.52	0.56	0.59	3.48	0.58	2.0294
A. occidentale	0.52	0.51	0.71	0.79	0.49	0.52	3.54	0.59	2.1692
A. indica	0.60	0.59	0.48	0.54	0.54	0.37	3.12	0.52	1.6586
M. indica	0.92	0.72	0.90	0.86	0.52	0.64	4.56	0.76	3.5944
C. dactylon	0.34	0.56	0.34	0.39	0.17	0.18	1.98	0.33	0.7582
S. officinarium	0.66	0.49	0.43	0.54	0.45	0.73	3.30	0.55	1.8876
P. notatum	0.39	0.37	0.57	0.21	0.34	0.22	2.10	0.35	0.822
P. purpureum	0.32	0.27	0.31	0.29	0.31	0.30	1.80	0.30	0.5416
C. zizaniodes	0.66	0.44	0.29	0.32	0.24	0.21	2.16	0.36	0.9174

Over all total of Root Density (RTD) = 3.48+3.36+3.0+3.48+3.54+ 3.12+4.56+ 1.98 +3.30+2.10+1.8+2.16 = 35.88 g/cm^3.

Over all mean of Root Density = 35.88/ (12x6) = 0.498 g/cm^3.

Sum of squares of the 72 data = 19.9868.

Correction factor = 35.88^2/ (12x6) = 17.8802.

$n\Sigma x_i^2 = 6(0.58^2+0.56^2+0.5^2+0.58^2+0.59^2+0.52^2+0.76^2+0.33^2+0.55^2+0.35^2+0.30^2+0.36^2)$

= 19.116.

Total variation = 19.9868 – 17.8802 = 2.1066.

Species variation = 19.116 - 17.8802 = 1.2358

Residual variation (within species) = 2.1066 – 1.2358 = 0.8708.

Table4.65: ANOVA Result of Root Density (RTD) (g/cm^3)

Source of variation	Sum of squares	Degree of freedom	Mean square	F- value
Between species	1.2358	11	0.1123	7.739
Residual (Within species)	0.8708	60	0.01451	
Total	2.1066	71		

From Table 4. 65, F-value of Root density is 7.739. From upper percentage points of F-Distribution, $F_{0.05,11,60} = 1.96$. By comparison F-value for Root density is greater than $F_{0.05,11,60}$, which shows that there is significant difference in Root density for the twelve species. In other words, Root density has played a significant role in the observed difference in the uprooting resistance of the twelve species.

4.2.4.7 Analysis of Variance on Specific Root Length (SRL) of the twelve species.

The Specific root length (SRL) is measured as the ratio of the total root length (L) to the total dry root weight (DWR). The Specific root length (SRL) of the six tested samples of the twelve species is shown in Table 4.66.

Table4.66: ANOVA on Specific Root Length (SRL) (cm/g)

Plant Species	SRL (cm/g)						Row total	Row average	Sum of Row square
	1	2	3	4	5	6			
O. abyssinica	4.17	3.59	4.44	3.36	2.41	2.31	20.28	3.38	72.4244
V. amygdalina	3.66	3.86	2.82	3.30	4.04	3.86	21.54	3.59	78.3588
M. excelsa	3.75	3.65	2.33	3.34	3.04	2.13	18.24	3.04	57.748
C. sinensis	2.95	2.50	2.63	2.36	2.52	2.70	15.66	2.61	41.0794
A. occidentale	2.07	1.94	2.73	3.03	1.85	1.88	13.50	2.25	31.6392
A. indica	2.76	2.69	2.20	2.48	2.45	1.70	14.28	2.38	34.7366
M. indica	3.48	2.72	3.41	3.28	1.97	2.42	17.28	2.88	51.6326
C. dactylon	4.90	7.96	4.77	5.51	2.45	2.61	28.20	4.7	153.2992
S. officinarium	4.68	3.47	3.02	3.77	3.20	5.08	23.22	3.87	93.323
P. notatum	4.08	5.26	8.16	2.96	4.80	4.62	29.88	4.98	164.0456
P. purpureum	5.54	4.61	5.38	5.00	5.23	5.02	30.78	5.13	158.4414
C. zizaniodes	7.40	4.93	3.29	3.56	2.74	2.32	24.24	4.04	115.4526

Over all total of specific root length = 20.28+21.54+18.24+15.66+13.5+14.28+17.28 +28.2+23.22 +29.88+30.78+24.24 = 257.1 cm/g.

Over all mean of specific root length = 257.1/ (12x6) = 3.57 cm/g.

Sum of squares of the 72 data = 1052.1808.

Correction factor = 257.1^2/ (12x6) = 918.06125.

$n\Sigma x_i^2$= $6(3.38^2+3.59^2+3.04^2+2.61^2+2.25^2+2.38^2 +2.88^2 +4.7^2+3.87^2+4.98^2+5.13^2+4.04^2)$ = 983.3598.

Total variation = 1052.1808 – 918.06125 = 134.1196.

Species variation = 983.3598 - 918.06125 = 65.2986

Residual variation (within species) = 134.1193 – 65.2986 = 68.8207.

Table 4.67: ANOVA Result of Specific Root Length Density (SRL) (cm/g)

Source of variation	Sum of squares	Degree of freedom	Mean square	F- value
Between species	65.2986	11	5.9362	5.175
Residual (Within species)	68.8207	60	1.1470	
Total	134.1196	71		

From Table 4.67, F-value of Specific root length is 5.175. From upper percentage points of F-Distribution, $F_{0.05,11,60}$ = 1.96. By comparison F-value for Root density is greater than $F_{0.05,11,60}$, which shows that there is significant difference in Specific root length for the twelve species. In other words, Specific root length has played a significant role in the observed difference in the uprooting resistance of the twelve species.

4.2.4.8 Analysis of Variance on – Percentage Fine Roots < 0.5mm (%FR<0.5mm) of the twelve species.

The Percentage Fine Roots (%FR) is measured as the percentage of the weight of fine roots less than 0.05mm to the total weight of the root. The Percentage Fine Roots of the six tested samples of the twelve species is shown in Table 4.68.

Table 4.68: Percentage Fine Roots< 0.5mm (%FR<0.5mm)

Plant Species	Percentage Fine Roots						Row total	Row average	Row square sum
	1	2	3	4	5	6			
O. abyssinica	30.06	41.91	28.90	44.8	52.03	55.5	253.2	42.2	11289.6726
V. amygdalina	38.18	36.17	39.97	37.96	27.91	32.81	213.0	35.5	7660.0080
M. excelsa	25.20	27.60	43.20	36.00	39.60	44.40	216.0	36.0	8098.5600
C. sinensis	38.36	42.89	41.08	43.80	48.03	40.84	255.0	42.5	10891.8346
A. occidentale	33.12	35.42	32.25	31.68	51.83	46.70	231.0	38.5	9262.4346
A. indica	24.71	35.63	36.04	31.92	39.13	40.17	207.6	34.6	7342.6348

M. indica	28.81	48.02	35.66	39.79	51.04	49.88	253.2	42.2	11083.9122
C. dactylon	82.16	42.14	84.27	45.30	86.45	85.08	425.4	70.9	32391.777
S. officinarium	65.76	77.55	82.90	71.35	86.17	83.87	477.6	79.60	38584.4584
P. notatum	93.84	82.73	82.79	92.3	90.50	73.89	516.1	86.01	44673.6547
P. purpureum	75.84	89.02	81.33	76.82	68.19	48.00	439.2	73.2	33146.0234
C. zizaniodes	66.0	65.72	64.65	72.86	89.29	82.50	441.0	73.5	32942.2746

Over all total of Percentage fine roots = 253.2+213+216+255+231+207.6+253.2+ 425.4+477.6+516.1+439.2+441= 3928.3.

Over all mean of percentage fine roots = 3928.3/ (12x6) = 54.56%.

Sum of squares of the 72 data = 247367.2449.

Correction factor = 3928.3^2/ (12x6) = 214326.9568.

$n\Sigma x_i^2 = 6(42.2^2+35.5^2+36^2+42.5^2+38.5^2+34.6^2 +42.2^2 +70.9^2+79.6^2+86.01^2+73.2^2+73.5^2)$ = 240748.6206.

Total variation= 247367.2449 – 214326.9568 = 33040.2881.

Species variation = 240748.6206 - 214326.9568 = 26421.6638.

Residual variation (within species) = 33040.2881 – 26421.6638 = 6618.6243.

Table 4.69: ANOVA on Percentage Fine Roots< 0.5mm (%FR<0.5mm)

Source of variation	Sum of squares	Degree of freedom	Mean square	F- value
Between species	26421.6638	11	2401.9694	21.775
Residual(Within species)	6618.6243	60	110.3104	
Total	33040.2881	71	*******	

From Table 4.69, F-value of Percentage fine roots is 21.775. From upper percentage points of F-Distribution, $F_{0.05,11,60}$ = 1.96. By comparison F-value for Percentage fine roots is greater than $F_{0.05,11,60}$, which shows that there is significant difference in Percentage fine roots for the twelve species. In other words, Percentage fine root has played a significant role in the observed difference in the uprooting resistance of the twelve species.

The summary of ANOVA on the eight morphological traits of the twelve species studied separately and when classed into two groups depending on resistance to lateral uprooting is presented in Table 4.70

Table 4.70: Plant Traits of the 12 Species Studied separately and when classed into two Groups Depending on Resistance to Lateral Uprooting and Result of ANOVA

Species/Re-sistance Group	H/D (cm/cm)	LR_1/D (cm/cm)	V/D (cm^3/cm)	DWR/D (g/cm)	% DWR_1	RTD g/cm^3	SRL cm/g	%FR <0.5mm
O. abyssinica	46.58	21.43	0.62	0.36	0.15	0.58	3.38	62.2
V. amygdalina	35.23	71.5	0.5	0.28	0.50	0.56	3.59	45.5
M. excelsa	40.33	72.0	0.22	0.11	0.88	0.50	3.04	36.0
C. sinensis	34.68	37.2	0.24	0.14	0.63	0.58	2.61	42.5
A. occidentale	33.84	53.1	0.33	0.13	0.70	0.59	2.25	38.5
A. indica	28.87	45.8	0.18	0.14	0.75	0.52	2.38	34.6
M. indica	35.44	46.9	0.34	0.26	0.58	0.76	2.88	42.2
Group 1	36.42	49.70	0.35	0.20	0.60	0.58	2.88	43.07
C. dactylon	42.08	21.7	0.24	0.08	0.25	0.33	4.70	80.9
S. officinarium	37.61	34.6	0.11	0.06	0.26	0.55	3.87	79.6
P. notatum	31.68	24.0	0.20	0.07	0.25	0.35	4.98	88.8
P. purpureum	51.09	26.8	0.30	0.10	0.22	0.30	5.13	73.2
C. zizaniodes	34.60	22.5	0.11	0.04	0.23	0.36	4.40	89.5
Group 2	39.41	25.92	0.19	0.07	0.24	0.38	4.62	82.4
ANOVA Btw Species	0.367	24.375	24.482	38.941	16.608	7.739	5.175	21.775
Coefficient of Correlation of Trait (r) With σ_{MAX}.	0.617	0.714	0.714	0.772	0.501	0.599	-0.63	-0.745

Group 1, with high critical stress, is characterized by high Root slenderness ratio LR_1/D, high Relative Root Dry Weight (DWR/D), high Percentage Tap root dry weight (%DWR1) ,high Root density (RTD),low Specific Root Length (SRL) and low percentage fine roots (%FR). Species from group 2, which were less resistant, invested less length and biomass in the tap root (low LR1/D and %DWR1) and were characterized with high Specific Root Length(SRL) and percentage of fine roots (%FR).

4.2.5 Multiple Regression and Correlation Analysis of Uprooting Resistance on the Morphological Traits

The uprooting resistance is affected by morphological traits. The nature of this relationship between the uprooting resistance and the morphological traits is investigated with multiple regression analysis.

Let $Y = \sigma_{max}$ (N/mm^2) = Uprooting resistance;

X_1 = H/D (cm/cm) = Plant slenderness ratio;

X_2 = LR_1/D (cm/cm) = Root slenderness ratio;

X_3 = V/D (cm^3/cm) = Root relative volume;

X_4 = DWR/D (g/cm) =Relative root dry weight;

X_5 = $\%DWR_1$ = Percentage tap root dry weight;

X_6 = SRL (cm/g) = Specific root length;

X_7 = %FR<0.5mm = Percentage fine roots < 0.5mm;

$X_8 = X_4/X_3$ = RTD = Root density.

4.2.5.1 Multiple Regression Analysis of Uprooting Resistance on the Morphological Traits for *O. abyssinica* Selected from group 1

Assuming the relationship between uprooting resistance and the morphological traits is linear; the form of the linear model is shown as equation (4.66).

$$Y = a_0+a_1X_1+a_2X_2+a_3X_3+a_4X_4+a_5X_5+a_6X_6+a_7X_7 \quad (4.66)$$

The applicable normal equations for obtaining estimates of a_0, a_1, a_2, a_3, a_4, a_5, a_6, and a_7 are as follows:

$$\Sigma Y = a_0N+a_1\Sigma X_1+a_2\Sigma X_2+a_3\Sigma X_3+a_4\Sigma X_4+a_5\Sigma X_5+a_6\Sigma X_6+a_7\Sigma X_7 \quad (4.67a)$$

$$\Sigma X_1Y=a_0\Sigma X_1+a_1\Sigma X_1^2+a_2\Sigma X_1X_2+a_3\Sigma X_1X_3+a_4\Sigma X_1X_4+a_5\Sigma X_1X_5+a_6\Sigma X_1X_6+a_7\Sigma X_1X_7; (4.67b)$$

$$\Sigma X_2Y= a_0\Sigma X_2+a_1\Sigma X_1X_2+a_2\Sigma X_2^2+a_3\Sigma X_2X_3+a_4\Sigma X_2X_4+a_5\Sigma X_2X_5+a_6\Sigma X_2X_6+a_7\Sigma X_2X_7; (4.67c)$$

$$\Sigma X_3Y =a_0\Sigma X_3+a_1\Sigma X_3X_1+a_2\Sigma X_2X_3+a_3\Sigma X_3^2+a_4\Sigma X_3X_4+a_5\Sigma X_3X_5+a_6\Sigma X_3X_6+a_7\Sigma X_3X_7; (4.67d)$$

$$\Sigma X_4Y =a_0\Sigma X_4+a_1\Sigma X_1X_4+a_2\Sigma X_2X_4+a_3\Sigma X_3X_4+a_4\Sigma X_4^2+a_5\Sigma X_4X_5+a_6\Sigma X_4X_6+a_7\Sigma X_4X_7; (4.67e)$$

$$\Sigma X_5Y =a_0\Sigma X_5+a_1\Sigma X_1X_5+a_2\Sigma X_2X_5+a_3\Sigma X_3X_5+a_4\Sigma X_4X_5+a_5\Sigma X_5^2+a_6\Sigma X_5X_6+a_7\Sigma X_5X_7; (4.67f)$$

$$\Sigma X_6Y =a_0\Sigma X_6+a_1\Sigma X_1X_6+a_2\Sigma X_2X_6+a_3\Sigma X_3X_6+a_4\Sigma X_4X_6+a_5\Sigma X_5X_6+a_6\Sigma X_6^2+a_7\Sigma X_6X_7; (4.67g)$$

$$\Sigma X_7Y =a_0\Sigma X_7+a_1\Sigma X_1X_7+a_2\Sigma X_2X_7+a_3\Sigma X_3X_7+a_4\Sigma X_4X_7+a_5\Sigma X_5X_7+a_6\Sigma X_6X_7+a_7\Sigma X_7^2; (4.67h)$$

The terms of Equation (4.67a), Equation (4.67b), Equation (4.67c), Equation (4.67d), Equation (4.67e), Equation (4.67f), Equation (4.67g) and Equation (4.67h) are evaluated as shown in Table 4.71.

Table 4.71: Evaluated Terms for Linear Regression of *O. abyssinica* Uprooting Resistance on Morphological traits; Selected from Resistance Group 1

Variables	Test no						Row sum	Sum of row squares
	1	2	3	4	5	6		
Y	3.1	1.11	2.93	4.05	4.59	4.93	20.71	81.2
X_1	47.22	31.94	47.4	52.76	50.96	53	283.3	13686

X_2	26.42	22.75	28.18	21.28	15.27	14.68	128.6	2911
X_3	0.76	0.66	0.82	0.62	0.44	0.42	3.72	2.44
X_4	0.44	0.38	0.47	0.36	0.26	0.25	2.16	0.819
X_5	0.18	0.16	0.2	0.15	0.11	0.1	0.9	0.143
X_6	4.17	3.59	4.44	3.36	2.41	2.31	20.28	72.42
X_7	30.06	41.91	28.9	44.8	52.03	55.5	253.2	11290
X_1X_2	1248	726.6	1336	1123	778.2	778	5989	6E+06
X_1X_3	35.89	21.08	38.87	32.71	22.42	22.26	173.2	5311
X_1X_4	20.78	12.14	22.28	18.99	13.25	13.25	100.7	1787
X_1X_5	8.5	5.11	9.48	7.914	5.606	5.3	41.91	310.4
X_1X_6	196.9	114.7	210.5	177.3	122.8	122.4	944.5	2E+05
X_IX_7	1419	673.3	1842	2364	2651	2942	11892	3E+07
X_2X_3	20.08	15.02	23.11	13.19	6.719	6.166	84.28	1420
X_2X_4	11.62	7.661	13.24	7.661	3.97	3.67	47.83	456.9
X_2X_5	4.756	3.64	5.636	3.192	1.68	1.468	20.37	82.8
X_2X_6	110.2	81.67	125.1	71.5	36.8	33.91	459.2	42080
X_2X_7	794.2	953.5	814.4	953.3	794.5	814.7	5125	4E+06
X_3X_4	0.334	0.251	0.385	0.223	0.114	0.105	1.413	0.397
X_3X_5	0.137	0.106	0.164	0.093	0.048	0.042	0.59	0.07
X_3X_6	3.169	2.369	3.641	2.083	1.06	0.97	13.29	35.31
X_3X_7	22.85	27.66	23.7	27.78	22.89	23.31	148.2	3688
X_4X_5	0.079	0.061	0.094	0.054	0.029	0.025	0.342	0.023
X_4X_6	1.835	1.364	2.087	1.21	0.627	0.578	7.7	11.77
X_4X_7	13.23	15.93	13.58	16.13	13.53	13.88	86.27	1249
X_5X_6	0.751	0.574	0.888	0.504	0.265	0.231	3.213	2.06
X_5X_7	5.411	6.706	5.78	6.72	5.723	5.55	35.89	216.4
X_6X_7	125.4	150.5	128.3	150.5	125.4	128.2	808.2	1E+05

X_1Y	146.4	35.45	138.9	213.7	233.9	261.3	1030	2E+05
X_2Y	81.9	25.25	82.57	86.18	70.09	72.37	418.4	31740
X_3Y	2.356	0.733	2.403	2.511	2.02	2.071	12.09	26.54
X_4Y	1.364	0.422	1.377	1.458	1.193	1.233	7.047	9.004
X_5Y	0.558	0.178	0.586	0.608	0.505	0.493	2.927	1.554
X_6Y	12.93	3.985	13.01	13.61	11.06	11.39	65.98	789.6
X_7Y	93.19	46.52	84.68	181.4	238.8	273.6	918.3	2E+05

The resulting normal equations with direct substitution of terms in Table 4.71 into Equation (4.67a) to Equation (4.67h) are:

$$20.71 = 6a_0+283.3a_1+128.6a_2+3.72a_3+2.16a_4+0.9a_5+20.28a_6+253.2a_7 \quad (4.68a)$$

$$1030 = 283.3a_0+3686.19a_1+5989a_2+173.2a_3+100.7a_4+41.91a_5+44.5a_6+11892a_7 \quad (4.68b)$$

$$418.4 = 128.6a_0+5989a_1+2911a_2+84.28a_3+47.83a_4+20.37a_5+459.2a_6+5125a_7 \quad (4.68c)$$

$$12.09 = 3.72a_0+173.2a_1+84.2a_2+2.44a_3+1.413a_4+0.59a_5+13.29a_6+148.2a_7 \quad (4.68d)$$

$$7.047 = 2.16a_0+100.7a_1+47.83a_2+1.413a_3+0.819a_4+0.342a_5+7.7a_6+86.27a_7 \quad (4.68e)$$

$$2.927 = 0.9a_0+41.91a_1+20.37a_2+0.59a_3+0.342a_4+0.143a_5+3.213a_6+35.89a_7 \quad (4.68f)$$

$$65.98 = 20.28a_0+944.5a_1+459.2a_2+13.29a_3+7.7a_4+3.213a_5+72.42a_6+808.2a_7 \quad (4.68g)$$

$$18.3 = 253.2a_0+11892a_1+5125a_2+148.2a_3+86.27a_4+35.89a_5+808.2a_6+11290a_7 \quad (4.68h)$$

Solving for the unknown coefficients of Equations (4.68a), (4.68b), (4.68c), (4.68d), (4.68e), (4.68f), (4.68g) and(4.68h) (see matrix A.21 in Appendix A) , we have that:

$a_0 = 15.6264$; $a_1 = 0.0409$; $a_2 = -0.0533$; $a_3 = 78.3097$; $a_4 = -1.1412$; $a_5 = -33.2464$; $a_6 = -15.0695$ and $a_7 = -0.1228$.

Therefore:

$$Y = 15.6264 + 0.0409X_1 - 0.0533X_2 + 78.3097X_3 - 1.1412X_4 - 33.246X_5 - 15.0695X_6 - 0.1228X_7$$

That is:

$$\sigma_{max} = 15.6264 + 0.0409(H/D) - 0.0533(LR_1/D) + 78.3097(V/D) - 1.1412(DWR/D) - 33.246(\%DWR_1) - 15.0695(SRL) - 0.1228(\%FR). \quad (4.69)$$

Coefficient of Determination (r^2) = 0.9788 and the Probability level, p = 0.0001451.

Assuming non linear regression model of the form;

$$\sigma_{max} = C(H/D)^{a_1} * (LR_1/D)^{a_2} * (V/D)^{a_3} * (DWR/D)^{a_4} * (\%DWR_1)^{a_5} * (SRL)^{a_6} * (\%FR)^{a_7}; \quad (4.70a)$$

Equation(4.72a) can be linearized by taking logarithm of both sides. That is:

$$Log\sigma_{max} = LogC + a_1Log(H/D) + a_2Log(LR_1/D) + a_3Log(V/D) + a_4Log(DWR/D) + a_5Log(\%DWR_1) + a_6Log(SRL) + a_7Log(\%FR). \quad (4.70b)$$

Let $Log\sigma_{max} = Y$, $LogC = a_0$, $Log(H/D) = X_1$, $Log(LR_1/D) = X_2$, $Log(V/D) = X_3$, $Log(DWR/D) = X_4$, $Log(\%DWR_1) = X_5$, $Log(SRL) = X_6$ and $Log(\%FR) = X_7$.

The linearized form of Equation (4.70a) is thus:

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 + a_5X_5 + a_6X_6 + a_7X_7. \quad (4.70c)$$

The applicable normal equations for obtaining estimates of the unknowns in Equation (4.70c) are Equations (4.67a), (4.67b), (4.67c), (4.67d), (4.67e), (4.67f), (4.67g) and (4.67h). The terms of Equations (4.67a), (4.67b), (4.67c), (4.67d), (4.67e), (4.67f), (4.67g) and (4.67h) for Non linear regression of *O. abyssinica* selected from resistance group 1are evaluated as shown in Table 4.72.

Table 4.72: Evaluated Terms for Non Linear Regression of *O. abyssinica* Uprooting Resistance on the Morphological Traits; Selected from Resistance Group 1

Variables	Test no						sum of row	Sum Of Row Square
	1	2	3	4	5	6		
Y	0.4914	0.453	0.4669	0.6075	0.6618	0.6928	3.3736	1.9519
X_1	1.6741	1.504	1.6758	1.7223	1.7072	1.7243	10.008	16.728
X_2	1.4219	1.357	1.4499	1.3280	1.1838	1.1667	7.9073	10.492
X_3	-0.1192	-0.181	-0.086	-0.2076	-0.357	-0.3768	-1.327	0.3664
X_4	-0.3565	-0.420	-0.328	-0.4437	-0.585	-0.6021	-2.735	1.3128
X_5	-0.7447	-0.796	-0.699	-0.8239	-0.959	-1.0000	-5.022	4.2744
X_6	0.6201	0.555	0.6474	0.5263	0.3820	0.3636	3.0945	1.6669
X_7	1.4780	1.622	1.4609	1.6513	1.7163	1.7443	9.6731	15.666
X_1X_2	2.3804	2.041	2.4297	2.2872	2.0210	2.0117	13.171	29.099
X_1X_3	-0.1996	-0.275	-0.144	-0.3575	-0.609	-0.6497	-2.231	1.0548
X_1X_4	-0.5968	-0.632	-0.549	-0.7642	-0.999	-1.0382	-4.579	3.7170
X_1X_5	-1.2467	-1.197	-1.171	-1.4190	-1.637	-1.7243	-8.395	12.025
X_1X_6	1.0381	0.835	1.0849	0.9064	0.6522	0.6270	5.1436	4.5920
X_1X_7	2.4743	2.440	2.4482	2.8440	2.9301	3.0077	16.145	43.792
X_2X_3	-0.1695	-0.245	-0.125	-0.2757	-0.422	-0.4396	-1.677	0.5517
X_2X_4	-0.5069	-0.570	-0.475	-0.5892	-0.693	-0.7025	-3.537	2.1284
X_2X_5	-1.0589	-1.080	-1.014	-1.0941	-1.135	-1.1667	-6.548	7.1609
X_2X_6	0.8817	0.753	0.9387	0.6989	0.4522	0.4242	4.1490	3.0989
X_2X_7	2.1016	2.202	2.1182	2.1929	2.0318	2.0351	12.681	26.828
X_3X_4	0.0425	0.076	0.0283	0.0921	0.2086	0.2269	0.6741	0.1118
X_3X_5	0.0888	0.144	0.0602	0.1710	0.3417	0.3768	1.1823	0.3202
X_3X_6	-0.0739	-0.100	-0.056	-0.1093	-0.136	-0.1370	-0.612	0.0679
X_3X_7	-0.1762	-0.293	-0.126	-0.3428	-0.612	-0.6573	-2.207	1.0565
X_4X_5	0.2655	0.334	0.2292	0.3656	0.5608	0.6021	2.3576	1.0455
X_4X_6	-0.2211	-0.233	-0.212	-0.2335	-0.224	-0.2189	-1.343	0.3007
X_4X_7	-0.5269	-0.682	-0.479	-0.7327	-1.004	-1.0502	-4.475	3.6197
X_5X_6	-0.4618	-0.442	-0.453	-0.4336	-0.366	-0.3636	-2.519	1.0675
X_5X_7	-1.1007	-1.291	-1.021	-1.3605	-1.645	-1.7443	-8.163	11.522

X_6X_7	0.9165	0.901	0.9458	0.8691	0.6556	0.6342	4.9218	4.1329
X_1Y	0.8227	0.682	0.7824	1.0463	1.1298	1.1946	5.6575	5.5520
X_2Y	0.6987	0.615	0.6770	0.8068	0.7834	0.8083	4.3892	3.2427
X_3Y	-0.0586	-0.088	-0.040	-0.1261	-0.236	-0.2610	-0.804	0.1515
X_4Y	-0.1752	-0.190	-0.153	-0.2695	-0.387	-0.4171	-1.593	0.4869
X_5Y	-0.3659	-0.361	-0.326	-0.5005	-0.634	-0.6928	-2.881	1.5035
X_6Y	0.3047	0.252	0.3023	0.3197	0.2528	0.2519	1.6830	0.4771
X_7Y	0.7263	0.735	0.6821	1.0032	1.1358	1.2085	5.4911	5.2901

The resulting normal equations with direct substitution of terms in Table 4.72 into Equation (4.67a) to Equation (4.67h) are:

$$3.3736 = 6a_0+10.008a_1+7.9073a_2 -1.3268a_3 -2.7354a_4 -5.0221a_5 +3.0945a_6 + 9.6731a_7 \quad (4.71a)$$

$$5.6575 = 10.008a_0+16.7279a_1+13.1714a_2-2.2314a_3 -4.5795a_4-8.3952a_5 +5.144a_6+ 16.145a_7 \quad (4.71b)$$

$$4.3892 = 7.9073a_0+13.1714a_1+10.4916a_2 -1.6767a_3-3.5368a_4-6.548a_5+4.149a_6 + 12.6809a_7 \quad (4.71c)$$

$$-0.8037 = -1.3268a_0 -2.2314a_1-1.6767a_2+0.3664a_3+0.6741a_4+1.1823a_5-0.6124a_6 - 2.2068a_7 \quad (4.71d)$$

$$-1.5926 = -2.7354a_0 -4.5795a_1-3.5368a_2+0.6741a_3+1.3128a_4+2.3576a_5 -1.3425a_6 - 4.4746a_7 \quad (4.71e)$$

$$-2.8807 = -5.0221a_0 -8.3952a_1-6.5480a_2+1.1823a_3+2.3576a_4+4.2744a_5-2.5195a_6 - 8.1531a_7 \quad (4.71f)$$

$$1.683 = 3.0945a_0+5.1436a_1+4.149a_2 - 0.6124a_3 -1.3425a_4- 2.5195a_5 +1.6669a_6+ 4.9218a_7 \quad (4.71g)$$

$$5.4911 = 9.6731a_0+16.1447a_1+12.6809a_2-2.2068a_3-4.4746a_4-8.163a_5 +4.9218a_6+ 15.6656a_7 \quad (4.71h)$$

Solving for the unknown coefficients of Equations (4.71a), (4.71b), (4.71c), (4.71d), (4.71e), (4.71f), (4.71g) and (4.71h), (See matrices (A.22) of Appendix A), we have:

$a_0 = 51.8463$; $a_1 = -8.2144$; $a_2 = 6.2016$; $a_3 = -47.6102$; $a_4 = 33.9609$; $a_5 = 22.8942$; $a_6 = -22.1983$ and $a_7 = -6.3186$. Therefore $LogC = a_0 = 51.8463$; $C = 7.0194x10^{51}$.

$$\therefore \sigma_{MAX} = 7.0194x10^{51}(H/D)^{\mathbf{-8.2144}}{}_*(LR_1/D)^{\mathbf{6.2016}}{}_*(V/D)^{\mathbf{-47.6102}}{}_*(DWR/D)^{\mathbf{33.9609}}{}_*$$

$$(\%DWR_1)^{\mathbf{22.8942}}{}_*(SRL)^{\mathbf{-22.1983}}{}_*(\%FR)^{\mathbf{-6.3186}}; \qquad (4.72)$$

Coefficient of Determination (r^2) = 0.784 and the Probability level, p = 0.020016.

The summary of the two multiple regression models of uprooting resistance (σ_{MAX}) on the morphological traits for *O. abyssinica* species selected from resistance group1 is presented in Table 4.73.

Table 4.73: Summary of Regression Analysis of Uprooting resistance (σ_{MAX}) on the morphological traits for *O. abyssinica* species selected from resistance group 1

Model	Equation	Coefficient of Determination (r^2)	Probability level (p)
Linear model	σ_{max} = 15.6264 +0.0409(H/D) – 0.0533(LR_1/D) + 78.3097(V/D)- 1.1412(DWR/D) -33.246 (%DWR_1) – 15.0695(SRL)–0.1228(%FR).	0.9783	0.0001451
Non linear model	$\sigma_{MAX} = 7.0194\text{x}10^{51}(H/D)^{-8.2144} {*} (LR_1/D)^{6.2016} {*} (V/D)^{-47.6102} {*} (DWR/D)^{33.9609} {*} (\%DWR_1)^{22.8942} {*} (SRL)^{-22.1983} {*} (\%FR)^{-6.3186}$	0.784	0.020016

Comparing the two models of Table 4.73, there is higher linear relationship between Uprooting resistance (σ_{MAX}) and the morphological traits for *O. abyssinica* species selected from resistance group 1.

4.2.5.2 Multiple Regression Analysis of Uprooting Resistance on the Morphological Traits for *S. officinarium* Selected from group 2.

Assuming the relationship between uprooting resistance and the morphological traits is linear; the form of the multiple linear model of Equation (4.66) is applicable.

The applicable normal equations for obtaining estimates of a_0, a_1, a_2, a_3, a_4, a_5, a_6 and a_7 as contained in Equation (4.66) are Equations (4.67a) to Equation (4.67h).

The terms of Equation (4.67a), Equation (4.67b), Equation (4.67c), Equation (4.67d), Equation (4.67e), Equation (4.67f), Equation (4.67g) and Equation (4.67h) for *S.Officinarium* selected from resistance group2 are evaluated as shown in Table 4.74.

Table 4.74: Evaluated Terms for Linear Regression of Uprooting Resistance on the Morphological Traits for *S. officinarium;* Selected from Resistance Group 2

Variables	Test no						Row sum	Row Square Sum
	1	2	3	4	5	6		
Y	0.95	1.2	1.21	1.14	2.1	1.1	7.7	10.726
X_1	48.39	43.48	45	52	45.75	49.11	283.7	13466
X_2	41.8	31.01	26.97	33.71	28.59	45.52	207.6	7462.1
X_3	0.14	0.1	0.09	0.11	0.09	0.13	0.66	0.0748
X_4	0.07	0.05	0.05	0.06	0.05	0.08	0.36	0.0224
X_5	0.3	0.22	0.19	0.24	0.21	0.34	1.5	0.3918
X_6	4.68	3.47	3.02	3.77	3.2	5.08	23.22	93.323
X_7	65.76	77.55	82.9	71.35	96.17	83.87	477.6	38584
X_1X_2	2023	1348	1214	1753	1308	2235	9881	2E+07
X_1X_3	6.775	4.348	4.05	5.72	4.118	6.384	31.39	171.64
X_1X_4	3.387	2.174	2.25	3.12	2.288	3.929	17.15	51.667
X_1X_5	14.52	9.566	8.55	12.48	9.608	16.7	71.42	902.4
X_1X_6	226.5	150.9	135.9	196	146.4	249.5	1105	214641
X_1X_7	3182	3372	3731	3710	4400	4119	22513	9E+07
X_2X_3	5.852	3.101	2.427	3.708	2.573	5.918	23.58	105.14
X_2X_4	2.926	1.551	1.349	2.023	1.43	3.642	12.92	32.188
X_2X_5	12.54	6.822	5.124	8.09	6.004	15.48	54.06	571.17
X_2X_6	195.6	107.6	81.45	127.1	91.49	231.2	834.5	134449
X_2X_7	2749	2405	2236	2405	2750	3818	16362	5E+07
X_3X_4	0.01	0.005	0.005	0.007	0.005	0.01	0.041	0.0003
X_3X_5	0.042	0.022	0.017	0.026	0.019	0.044	0.171	0.0055
X_3X_6	0.655	0.347	0.272	0.415	0.288	0.66	2.637	1.3142
X_3X_7	9.206	7.755	7.461	7.849	8.655	10.9	51.83	455.88
X_4X_5	0.021	0.011	0.01	0.014	0.011	0.027	0.094	0.0017
X_4X_6	0.328	0.174	0.151	0.226	0.16	0.406	1.445	0.4022
X_4X_7	4.603	3.878	4.145	4.281	4.809	6.71	28.42	139.89
X_5X_6	1.404	0.763	0.574	0.905	0.672	1.727	6.045	7.136
X_5X_7	19.73	17.06	15.75	17.12	20.2	28.52	118.4	2442.9
X_6X_7	307.8	269.1	250.4	269	307.7	426.1	1830	578457
X_1Y	45.97	52.18	54.45	59.28	96.08	54.02	362	23464
X_2Y	39.71	37.21	32.63	38.43	60.04	50.07	258.1	11615

X_3Y	0.133	0.12	0.109	0.125	0.189	0.143	0.819	0.1158
X_4Y	0.067	0.06	0.061	0.068	0.105	0.088	0.448	0.0352
X_5Y	0.285	0.264	0.23	0.274	0.441	0.374	1.868	0.6133
X_6Y	4.446	4.164	3.654	4.298	6.72	5.588	28.87	145.31
X_7Y	62.47	93.06	100.3	81.34	202	92.26	631.4	78555

The resulting normal equations with direct substitution of terms in Table 4.74 into Equation (4.67a) to Equation (4.67h) are:

$$7.7 = 6a_0+283.7a_1+207.6a_2+0.66a_3+0.36a_4+1.5a_5+23.22a_6+477.6a_7 \quad (4.73a)$$

$$362 = 283.7a_0+13466a_1+9881a_2+31.39a_3+17.15a_4+71.42a_5+1105a_6+22513a_7 \quad (4.73b)$$

$$258.1 = 207.6a_0+9881a_1+7462a_2+23.58a_3+12.92a_4+54.06a_5+834.5a_6+16362a_7 \quad (4.73c)$$

$$0.819 = 0.66a_0+31.39a_1+23.58a_2+0.075a_3+0.041a_4+0.171a_5+2.637a_6+51.83a_7 \quad (4.73d)$$

$$0.448 = 0.36a_0+17.15a_1+12.92a_2+0.041a_3+0.022a_4+0.094a_5+1.445a_6+28.42a_7 \quad (4.73e)$$

$$1.868= 1.5a_0+71.42a_1+54.06a_2+0.171a_3+0.094a_4+0.392a_5+6.045a_6+118.4a_7 \quad (4.73f).$$

$$28.87 = 23.22a_0+1105a_1+834.5a_2+2.637a_3+1.445a_4+6.045a_5+93.32a_6+1830a_7 \quad (4.73g)$$

$$631.4 = 477.6a_0+2251a_1+16362a_2+51.83a_3+28.42a_4+118.4a_5+1830a_6+38584a_7 \quad (4.73h).$$

Solving for the unknown coefficients of Equation (4.73a), Equation (4.73b), Equation (4.73c), Equation (4.73d), Equation (4.73e), Equation (4.73f), Equation (4.73g), and Equation (4.73h), (See matrices (A.23) of Appendix A), we have: $a_0 = 1.5074$; $a_1 = -0.0042$; $a_2 = 0.2623$; $a_3 = -13.7774$; $a_4 = 5.0661$; $a_5 = 9.4290$; $a_6 = -2.9381$and $a_7 = 0.0141$.

$$\therefore Y = 1.5074 - 0.0042X_1 + 0.2623X_2 - 13.7774X_3 + 5.0661X_4 + 9.4290X_5 - 2.9381X_6 + 0.0141X_7 \quad (4.74a)$$

That is, σ_{max} = 1.5074 - 0.0042 (H/D)+ 0.2623 (LR_1/D) - 13.7774 (V/D) + 5.0661 (DWR/D) + 9.4290 (%DWR_1) - 2.9381 (SRL)+ 0.0141 (%FR) (4.74b)

Coefficient of Determination (r^2) = 0.9998 and the Probability level, p = 0.00000036.

For non linear regression model, Equation (4.70a) is applicable.

The applicable normal equations for estimating the unknowns of Equation (4.70a) are Equations (4.71a) to (4.71i);

The terms of Equation (4.71a) to Equation (4.71i), are evaluated as shown in Table 4.75.

Table 4.75: Evaluated Terms for Non Linear Regression of Uprooting Resistance on plant Morphological Traits for *S. officinarium;* Selected from Resistance Group 2

Variables	Test no						sum of row	Sum 0f Row Square
	1	2	3	4	5	6		
Y	0.02228	0.07918	0.08279	0.05690	0.32220	0.04139	0.60474	0.12238
X_1	1.6848	1.6383	1.6532	1.7160	1.6604	1.6912	10.0439	16.81739
X_2	1.6212	1.4915	1.4309	1.5278	1.4562	1.6582	9.18580	14.10466
X_3	-0.8539	-1.0000	-1.04580	-0.9586	-0.3565	-0.3768	-4.59160	4.01083
X_4	-1.1549	-1.3010	-1.3010	-1.2218	-1.3010	-1.0969	-7.37660	9.10758
X_5	-0.5229	-0.6576	-0.7212	-0.6198	-0.6778	-0.4685	-3.66780	2.28905
X_6	0.6702	0.5403	0.4800	0.5763	0.5051	0.7059	3.47780	2.05703
X_7	1.8180	1.8896	1.9186	1.8534	1.9830	1.9236	11.3862	21.62436
X_1X_2	2.7314	2.4435	2.3656	2.6217	2.4179	2.8043	15.3844	39.61106
X_1X_3	-1.4387	-1.6383	-1.7289	-1.6450	-0.5919	-0.6372	-7.68000	11.20525
X_1X_4	-1.9458	-2.1314	-2.1508	-2.0966	-2.1602	-1.8551	-12.3399	25.45849
X_1X_5	-0.8810	-1.0773	-1.1923	-1.0636	-1.1254	-0.7923	-6.13194	6.38390
X_1X_6	1.1292	0.8852	0.7935	0.9889	0.8387	1.1938	5.82928	5.79477
X_1X_7	3.0630	3.0957	3.1718	3.1804	3.2926	3.2532	19.0567	60.56528
X_2X_3	-1.3843	-1.4915	-1.4964	-1.4645	-0.5191	-0.6248	-6.98077	9.18509
X_2X_4	-1.8723	-1.9404	-1.8616	-1.8667	-1.8945	-1.8189	-11.2544	21.11842
X_2X_5	-0.8477	-0.9808	-1.0320	-0.9469	-0.9870	-0.7769	-5.57131	5.21997
X_2X_6	1.0865	0.8059	0.6868	0.8805	0.7355	1.1705	5.36574	4.98804
X_2X_7	2.9473	2.8183	2.7453	2.8316	2.8876	3.1897	17.4199	50.69752
X_3X_4	0.9862	1.3010	1.3606	1.1712	0.4638	0.4133	5.69609	6.27402
X_3X_5	0.4465	0.6576	0.7542	0.5941	0.2416	0.1765	2.87064	1.64322

X_3X_6	-0.5723	-0.5403	-0.5020	-0.5524	-0.1801	-0.2660	-2.61306	1.27978
X_3X_7	-1.5524	-1.8896	-2.0065	-1.7767	-0.7069	-0.7248	-8.65688	14.18810
X_4X_5	0.6039	0.8555	0.9383	0.7573	0.8818	0.5139	4.55070	3.59216
X_4X_6	-0.7740	-0.7029	-0.6245	-0.7041	-0.6571	-0.7743	-4.23698	3.01034
X_4X_7	-2.0996	-2.4584	-2.4961	-2.2645	-2.5799	-2.1100	-14.0084	32.91822
X_5X_6	-0.3504	-0.3553	-0.3462	-0.3572	-0.3424	-0.3307	-2.08219	0.72306
X_5X_7	-0.9506	-1.2426	-1.3837	-1.1487	-1.3441	-0.9012	-6.97095	8.30068
X_6X_7	1.2184	1.0210	0.9209	1.0681	1.0016	1.3579	6.58790	7.36291
X_1Y	0.0375	0.1297	0.1369	0.0976	0.5350	0.0700	1.00675	0.33761
X_2Y	0.0361	0.1181	0.1185	0.0869	0.4692	0.0686	0.89743	0.26169
X_3Y	-0.0190	-0.0792	-0.0866	-0.0545	-0.1149	-0.0156	-0.36979	0.03054
X_4Y	-0.0257	-0.1030	-0.1077	-0.0695	-0.4192	-0.0454	-0.77056	0.20548
X_5Y	-0.0117	-0.0521	-0.0597	-0.0353	-0.2184	-0.0194	-0.39647	0.05572
X_6Y	0.0149	0.0428	0.0397	0.0328	0.1627	0.0292	0.32220	0.03205
X_7Y	0.0405	0.1496	0.1588	0.1055	0.6389	0.0796	1.17296	0.47494

The resulting normal equations with direct substitution of terms in Table 4.75 into Equation (4.73b) to Equation (4.73i) are:

$0.60474 = 6a_0+10.0439a_1+9.1858a_2 -4.5916a_3 -7.3766a_4 -3.6678a_5 +3.4778a_6 + 11.3862a_7$ (4.75a)

$1.00675=10.0439a_0+16.81739a_1+15.384a_2-7.68a_3-12.3399a_4-6.13194a_5+5.829a_6+ 19.05673a_7$ (4.75b)

$0.8974=9.1858a_0+15.3844a_1+14.1047a_2-6.98077a_3-11.2544a_4-5.5713a_5+5.3666a_6+$

$17.4199a_7$ (4.75c)

$-0.36979 = -4.5916a_0 - 7.68a_1 - 6.98077a_2 + 4.01083a_3 + 5.6961a_4 + 2.8706a_5 - 2.61306a_6 - 8.65688a_7$ (4.76d)

$-0.7706 = -7.3766a_0 - 12.3399a_1 - 11.2544a_2 + 5.6961a_3 + 9.1076a_4 + 4.5507a_5 - 4.23698a_6 - 14.0084a_7$ (4.75e)

$-0.39647 = -3.6678a_0 - 6.13194a_1 - 5.5713a_2 + 2.8706a_3 + 4.5507a_4 + 2.289a_5 - 2.08219a_6 - 6.97095a_7$ (4.75f)

$0.3222 = 3.4778a_0 + 5.82928a_1 + 5.3657a_2 - 2.61306a_3 - 4.23698a_4 - 2.08219a_5 + 2.0570a_6 + 6.5879a_7$ (4.75g)

$1.17296 = 11.3862a_0 + 19.0567a_1 + 17.4199a_2 - 8.6569a_3 - 14.008a_4 - 6.97095a_5 + 6.5879a_6 + 21.624a_7$ (4.75h)

Solving for the unknown coefficients of Equation (4.75a), Equation (4.75b), Equation (4.75c), Equation (4.75d), Equation (4.75e), Equation (4.75f), Equation (4.75g) and Equation (4.75h), (See matrices (A.24) of Appendix A), we have:

$a_0 = -12.0255$; $a_1 = 2.2839$; $a_2 = 2.7471$; $a_3 = 0.2314$; $a_4 = -3.0253$; $a_5 = 0.0054$;

$a_6 = -1.1115$ and $a_7 = 0.6336$. Therefore LogC = $a_0 = -12.0255$; C = $9.43\text{x}10^{-13}$.

$\therefore \sigma_{MAX} = 9.43\text{x}10^{-13} (H/D)^{\mathbf{2.2839}} * (LR_1/D)^{\mathbf{2.7471}} * (V/D)^{\mathbf{0.2314}} * (DWR/D)^{\mathbf{-3.0253}} * (\%DWR_1)^{\mathbf{0.0054}} * (SRL)^{\mathbf{-1.1115}} * (\%FR)^{\mathbf{0.6336}}$; (4.76)

Coefficient of Determination (r^2) = 0.7236 and p = 0.02006.

The summary of the two multiple regression models of uprooting resistance (σ_{MAX}) on the morphological traits for *S. officinarium* species selected from resistance group 2 is presented in Table 4.76.

Table 4.76: Summary of Multiple Regression Analysis of Uprooting resistance (σ_{MAX}) on the morphological traits for *S. officinarium* species selected from resistance group 2

Model	Equation	Coefficient of Determination (r^2)	Probability level (p)

Linear model	σ_{max} = 1.5074 - 0.0042 (H/D)+ 0.2623 (LR_1/D) - 13.7774 (V/D) + 5.0661 (DWR/D) + 9.4290 (%DWR_1) - 2.9381 (SRL)+ 0.0141 (%FR)	0.9998	0.0000003 6
Non linear model	$\sigma_{MAX} = 9.43x10^{-13} (H/D)^{\mathbf{2.2839}} {*}(LR_1/D)^{\mathbf{2.7471}} {*}(V/D)^{\mathbf{0.2314}} {*}(DWR/D)^{\mathbf{-3.0253}} {*}(\%DWR_1)^{\mathbf{0.0054}} {*}(SRL)^{\mathbf{-1.1115}} {*}(\%FR)^{\mathbf{0.6336}}$	0.7236	0.02006

Comparing the two models of Table 4.76, there is higher linear relationship between Uprooting resistance (σ_{MAX}) and the morphological traits for *S. officinarium* species selected from resistance group 2. The appropriate multiple regression models that best describe the relationship between uprooting resistance (σ_{MAX}) and the morphological traits for both resistance group1 and resistance group 2 is presented in Table 4.77.

Table 4.77: Appropriate Regression models of uprooting resistance (σ_{MAX}) on the morphological traits for both resistance group1 and resistance group 2

Resistance group	Best model	Equation	Coefficient of Determination (r^2)	Probab ility level (p)
Group 1	Linear	σ_{max} = 15.6264 +0.0409(H/D) – 0.0533 (LR_1/D) + 78.3097(V/D)- 1.1412 (DWR/D) -33.246 (%DWR_1) – 15.0695 (SRL)–0.1228(%FR).	0.9783	0.0001 451
Group 2	Linear	σ_{max} = 1.5074 - 0.0042 (H/D)+ 0.2623 (LR_1/D) - 13.7774 (V/D) + 5.0661 (DWR/D) + 9.4290 (%DWR_1) - 2.9381 (SRL)+ 0.0141 (%FR)	0.9998	0.0000 0036

From Table 4.77, the relationships between the plants uprooting resistance (σ_{MAX}) and the morphological traits are all significant at 95% confidence level as confirmed by the various values of p ($P< 0.05$).

4.3 Discussion of Results

4.3.1 Uprooting Force/Uprooting Resistance.

Plants maximum uprooting force showed large inter-and intra-specific variability. Maximum uprooting force (F_{max}) ranged from 210N to 847 N (Table 4.2).

This large variability in F_{max} is mainly explained by the variation in D. Indeed, we found a linear positive relationship between F_{max} and D for all species. Root breakage generally occurred between 10 and 20 cm below the soil surface and the root system section dislodged from the soil consisted of the tap root, main lateral roots, and a few fine roots without soil particles. However, for *C. zizanioides,*'root balls', i.e. root-soil aggregates containing many fine roots were observed around the main root branches.

When F_{MAX} was normalized by stem basal cross-sectional area (σ: critical stress), the intra specific variability was lower.

The ANOVA analysis showed that the uprooting resistance σ_{MAX}; differed between species. The highest values were found in *O. abyssinica*(4.95MPa), and the lowest in *C. zizanioides*(0.24MPa). Species were classified into two resistance groups using Duncan's multiple range test:

– Group 1: *O. abyssinica, V. amygdalina, and M. excelsa, C. sinensis, A. occidentale, A. indica and M. indica.*

– Group 2: *S.officinarium, C. dactylon, P. notatum, P. purpureum and C. zizanioides.*

4.3.2 Plant Traits and Relationship with Resistance to Uprooting.

All traits differed significantly between species and between resistance groups (Table 4.68). For example, the root slenderness ratio (LR1/D) ranged from 11.3 (C. *dactylon*) to 88.8 (*M. excelsa*), the plant slenderness ratio, ie Shoot slenderness ratio (H/D) from

22.2 *(C. zizanioides)* to 53.0 (*O. abyssinica*) and the percentage of root biomass allocated to the tap root (%DWR1) from 0.10 (*C. zizanioides*) to 0.84 (*M. excelsa*).

Uprooting Resistance Group 1, with high critical stress, is characterized by high root slenderness ratio (LR1/D), high percentage tap root dry weight (% DWR_1), high relative root dry weight (DWR/D), low specific root length (SRL) and low percentage fine roots (FR <0.05mm). Species from Resistance group 2, which were less resistant, invested less length and biomass in the tap root (low LR1/D and %DWR1) and were characterized with high Specific Root Length(SRL) and percentage of fine roots (%FR) and high relative root volume (V/D). Finally, the plants uprooting resistances were related with the morphological traits using multiple regressions. The relationship was found to be non linear for both resistance groups.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

From the analysis of the result obtained from the morphological traits measurement and lateral in-situ uprooting tests carried out on the selected plant species growing in the case study area; the following can be deduced:

Plant morphological traits such as root slenderness ratio (LR_1/D), shoot slenderness ratio (H/D), relative root volume (V/D), relative root dry weight, percentage tap root dry weight ($\%DWR_1$), percentage fine roots(FR<0.05mm), root density(RTD) and specific root length (SLR) all have bearing effects on the plant resistance to uprooting.

While such morphological traits as root slenderness ratio, shoot slenderness ratio, relative root volume, relative root dry weight, percentage tap root dry weight and root density have positive effects on plant resistance to uprooting; high values of other traits such as percentage fine roots and specific root length have reduction effect on plant resistance to uprooting.

Plants such as *Oxysthentera abyssinica* (Bamboo), *Vernonia amygdalina* (bitter leaf plant), *Milicia excelsa* (African Teak plant) with high values of resistance to uprooting associated with high values of root slenderness ratio, shoot slenderness ratio, relative root volume, relative root dry weight, percentage tap root dry weight, root density and low values of percentage fine roots and specific root length are most suitable for use in erosion mitigation, flood control and land reclamation.

5.2 Recommendations

From the foregoing, we would wish to recommend thus:

(1) That those plant such as *Oxysthentera abyssinica, Vernonia amygdalina, Milicia excelsa*, *Citrus sinensis, Arachina indica, Magnifera indica, Anacardium occidentale* and *Cynodon dactylon* with high values of resistance to uprooting be incorporated into design plan of using vegetation to mitigate erosion, control flood and land reclamation.

(2) That hybrids and clones of plant species with the desirable traits of high root slenderness ratio, high values of shoot slenderness ratio, high values of relative root dry weight, high values of percentage tap root dry weight, high values of root density, low values of percentage fine roots and low values of specific root length be breed and incorporated into the design plan of using vegetation to mitigate erosion, control flood and land reclamation (Bioengineering).

For further knowledge and understanding of the topic, the following areas are recommended for further research studies:

(i) Relating soil geotechnical properties to the uprooting resistance of plants in erosion prone areas.

(ii) Carrying out lateral uprooting test on juvenile plants using advanced equipment with defined variation of speed of tensioning and studying its effect on the plants resistance to uprooting.

5.3 Contributions to Knowledge

The following contributions to knowledge have been made:

(i) Development of a defined relationship between plant morphological traits and the uprooting resistance of species that can be used in erosion mitigation, flood control and land reclamation.

(ii) Classification of plant species within the locality of the case study based on their resistances to uprooting from which selection can be made to be used in erosion mitigation, flood control and land reclamation.

(iii) Identification of plant morphological traits that favor high resistance to uprooting; so that plant hybrid and clones with these desirable traits can be bred and incorporated into design plan of mitigating erosion, flood control and land reclamation.

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APPENDIX A1

Matrices for *O. abyssinicca*

Matrix (A.1) is gotten by dividing Equations (4.7a), (4.7b) and (4.7c) by 6, 87.6 and 1351 respectively.

$$\begin{bmatrix} 1 & 14.6000 & 225.1667 \\ 1 & 15.4224 & 248.9412 \\ 1 & 16.1416 & 269.7966 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 548.8333 \\ 586.3470 \\ 621.9215 \end{bmatrix} \qquad (A.1)$$

By matrix triangulation of (A.1), (Gauss elimination technique), we obtain matrix (A.2).

$$\begin{bmatrix} 1 & 14.6000 & 225.1667 \\ 0 & 0.8224 & 23.7745 \\ 0 & 0 & 0.03429 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 548.8333 \\ 37.5137 \\ 1.4768 \end{bmatrix} \qquad (A.2)$$

Matrices of *O. abyssinicca`s* Cubic Regression Model

Matrix (A.3) is gotten by dividing Equations (4.11a), (4.11b), (4.11c) and (4.11d) by 6, 87.6, 1351 and 21807.252 respectively.

$$\begin{bmatrix} 1 & 14.6 & 225.1667 & 3634.542 \\ 1 & 15.4224 & 248.9412 & 4160.9037 \\ 1 & 16.1416 & 269.7966 & 4630.6886 \\ 1 & 16.7144 & 286.8798 & 5022.8888 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 548.8333 \\ 586.3470 \\ 621.9215 \\ 653.4291 \end{bmatrix} \qquad (A.3)$$

APPENDIX A2

By matrix triangulation (Gauss elimination technique) of matrix (A.3), we obtain matrix (A.4).

$$\begin{bmatrix} 1 & 14.6 & 225.1667 & 3634.542 \\ 0 & 0.8224 & 23.7745 & 526.3617 \\ 0 & 0 & 0.03429 & 5.0543 \\ 0 & 0 & 0 & -3.0112 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 548.8333 \\ 37.5137 \\ 1.4768 \\ -1.0021 \end{bmatrix} \quad (A.4)$$

Matrices for *C. sinensis*

Matrices for *C. sinensis`s* Quadratic Regression Model

Matrix (A.5) is gotten by dividing Equations (4.15a), (4.15b) and (4.15c) by 6, 84.4 and 1193respectively.

$$\begin{bmatrix} 1 & 14.0667 & 198.8333 \\ 1 & 14.1351 & 200.898 \\ 1 & 14.2127 & 203.033 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 400.1667 \\ 410.7701 \\ 421.8948 \end{bmatrix} \quad (A.5)$$

By matrix triangulation (Gauss elimination technique) of Matrix (A.5), we obtain Matrix (A.6).

$$\begin{bmatrix} 1 & 14.0667 & 198.8333 \\ 0 & 0.0684 & 2.0648 \\ 0 & 0 & -0.09807 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 400.1667 \\ 10.6034 \\ -0.4239 \end{bmatrix} \quad (A.6)$$

APPENDIX A3

Matrices of *C. sinensis*`*s* Cubic Regression Model

Matrix (A.7) is gotten by dividing Equations (4.17a), (4.17b), (4.17c) and (4.17d) by 6, 84.4, 1193 and 16955.8 respectively.

$$\begin{bmatrix} 1 & 14.0667 & 198.8333 & 2825.9667 \\ 1 & 14.1351 & 200.8981 & 2869.8623 \\ 1 & 14.2127 & 203.0313 & 2915.8320 \\ 1 & 14.2852 & 205.1562 & 2962.2423 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 401.6667 \\ 410.7701 \\ 421.8948 \\ 433.3023 \end{bmatrix} \quad (A.7)$$

By matrix triangulation (Gauss elimination technique) of Matrix (A.7), we obtain Matrix (A.8).

$$\begin{bmatrix} 1 & 14.0667 & 198.8333 & 2825.9667 \\ 0 & 0.0684 & 2.0648 & 43.8956 \\ 0 & 0 & -0.09807 & -1.7943 \\ 0 & 0 & 0 & 0.3766 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 401.6667 \\ 9.1034 \\ 0.3733 \\ 0.5446 \end{bmatrix} \quad (A.8)$$

Matrices for *V. amygdalina*

Matrices of *V. amygdalina*`*s* Quadratic Regression

Matrix (A.9) is gotten by dividing Equations (4.21a), (4.21b) and (4.21c) by 6, 95.3 and 1534 respectively.

$$\begin{bmatrix} 1 & 15.8833 & 255.6667 \\ 1 & 16.0965 & 261.9658 \\ 1 & 16.2749 & 267.5444 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 637.3333 \\ 646.5477 \\ 654.6975 \end{bmatrix} \quad (A.9)$$

APPENDIX A4

By matrix triangulation (Gauss elimination technique) of Matrix (A.9), we obtain Matrix (A.10).

$$\begin{bmatrix} 1 & 15.8833 & 255.6667 \\ 0 & 0.2132 & 6.2991 \\ 0 & 0 & 0.1708 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 637.3333 \\ 9.2144 \\ 0.2441 \end{bmatrix} \quad (A.10)$$

Matrices of *V. amygdalinas`s* Cubic Regression Model

Matrix (A.11) is gotten by dividing Equations (4.23a), (4.23b), (4.23c) and (4.23d) by 6, 95.3, 1534 and 24965.339 respectively

$$\begin{bmatrix} 1 & 15.8833 & 255.6667 & 4160.8898 \\ 1 & 16.0965 & 261.9658 & 4306.5391 \\ 1 & 16.2747 & 267.5444 & 4435.4357 \\ 1 & 16.4393 & 272.5362 & 4550.6841 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 637.3333 \\ 646.5477 \\ 654.6975 \\ 662.2394 \end{bmatrix} \quad (A.11)$$

By matrix triangulation (Gauss elimination technique) of Matrix (A.11), we obtain Matrix (A.12).

$$\begin{bmatrix} 1 & 15.8833 & 255.6667 & 4160.8898 \\ 0 & 0.2132 & 6.2991 & 145.6493 \\ 0 & 0 & 0.1708 & 3.8990 \\ 0 & 0 & 0 & -0.05338 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 637.3333 \\ 9.2144 \\ 0.2441 \\ 0.09418 \end{bmatrix} \quad (A.12)$$

APPENDIX A5

Matrices for A. *indica*

Matrices of *M. indica`s* Quadratic Regression

Matrix (A.13) is gotten by dividing Equations (4.47a), (4.47b) and (4.47c) by 6, 100.8 and 1731 respectively.

$$\begin{bmatrix} 1 & 16.8000 & 288.5 \\ 1 & 17.1726 & 300.2266 \\ 1 & 17.4829 & 310.0697 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 522.000 \\ 544.6726 \\ 563.1276 \end{bmatrix} \quad (A.13)$$

By matrix triangulation (Gauss elimination technique) of Matrix (A.13), we obtain Matrix (A.14).

$$\begin{bmatrix} 1 & 16.8 & 288.5 \\ 0 & 0.3726 & 11.7266 \\ 0 & 0 & 0.04214 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 522 \\ 22.6726 \\ -0.2328 \end{bmatrix} \quad (A.14)$$

Matrices of *A. indicas`s* Cubic Regression Model

Matrix (A.15) is gotten by dividing Equations (4.49a), (4.49b), (4.49c) and (4.49d) by 6, 95.3, 1534 and 24965.339 respectively.

$$\begin{bmatrix} 1 & 16.8 & 288.5 & 5043.807 \\ 1 & 17.1726 & 300.2266 & 5324.7092 \\ 1 & 17.4829 & 310.0697 & 5563.2846 \\ 1 & 17.7356 & 318.2135 & 5763.2107 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 522.000 \\ 544.6726 \\ 563.1276 \\ 577.7754 \end{bmatrix} \quad (A.15)$$

APPENDIX A6

By matrix triangulation (Gauss elimination technique) of Matrix (A.15), we obtain

Matrix (A.16).

$$\begin{bmatrix} 1 & 16.8 & 288.5 & 5043.807 \\ 0 & 0.3726 & 11.7266 & 280.9022 \\ 0 & 0 & 0.04214 & 2.5322 \\ 0 & 0 & 0 & -2.3111 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 522.000 \\ 22.6726 \\ -0.2328 \\ 0.2146 \end{bmatrix} \quad (A.16)$$

Matrices for *P. notatum*

Matrices of *P. notatum`s* Quadratic Regression

Matrix (A.17) is gotten by dividing Equations (4.57a), (4.57b) and (4.57c) by 6, 45.4 and 378.7 respectively.

$$\begin{bmatrix} 1 & 7.5667 & 63.1167 \\ 1 & 8.3414 & 76.6541 \\ 1 & 9.1896 & 92.0693 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 47.8833 \\ 53.0837 \\ 60.0797 \end{bmatrix} \quad (A.17)$$

By matrix triangulation (Gauss elimination technique) of Matrix (A.17), we obtain

Matrix (A.18).

$$\begin{bmatrix} 1 & 7.5667 & 63.1167 \\ 0 & 0.7747 & 13.5374 \\ 0 & 0 & 0.2833 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 47.8833 \\ 5.2004 \\ 0.6216 \end{bmatrix} \quad (A.18)$$

APPENDIX A7

Matrices of *P. notatum`s* Cubic Regression Model

Matrix (A.19) is gotten by dividing Equations (4.59a), (4.59b), (4.59c) and (4.59d) by 6, 45.4, 378.7 and 3480.094 respectively.

$$\begin{bmatrix} 1 & 7.5667 & 63.1167 & 580.0157 \\ 1 & 8.3414 & 76.6541 & 767.9881 \\ 1 & 9.1896 & 92.0693 & 988.8430 \\ 1 & 10.0189 & 107.6048 & 1215.900 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 47.8833 \\ 53.0837 \\ 60.0797 \\ 67.7521 \end{bmatrix} \quad \text{(A.19)}$$

By matrix triangulation (Gauss elimination technique) of Matrix (A.19), we obtain Matrix (A.20).

$$\begin{bmatrix} 1 & 7.5667 & 63.1167 & 580.0157 \\ 0 & 0.7747 & 13.5374 & 187.9724 \\ 0 & 0 & 0.2833 & 7.1835 \\ 0 & 0 & 0 & -0.1098 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} 47.8833 \\ 5.2004 \\ 0.6216 \\ -0.0320 \end{bmatrix} \quad \text{(A.20)}$$

APPENDIX A8

Matrices of Resistance Group 1 Linear Multiple Regression Analysis

Matrix (A.21) is gotten by dividing Equations (4.68a), (4.68b), (4.68c), (4.68d), (4.68e), (4.68f), (4.68g) and (4.68h) by 6, 283.3, 128.6, 3.72, 2.16, 0.9, 20.28 and 253.2 respectively.

				X						Y	
1	47.2167	21.4333	0.6200	0.3600	0.1500	3.3800	42.2000	a_0		3.4517	
1	48.3099	21.1401	0.6114	0.3555	0.1479	3.3339	41.9767	a_1		3.6357	
1	46.5708	22.6361	0.6554	0.3719	0.1584	3.5708	39.8523	a_2		3.2535	
1	46.5591	22.6559	0.6559	0.3798	0.1586	3.5726	39.8387	a_3	=	3.2500	[A.21]
1	46.6204	22.1435	0.6542	0.3792	0.1583	3.5648	39.9398	a_4		3.2625	
1	46.5667	22.6333	0.6556	0.3800	0.1589	3.5700	39.8778	a_5		3.2522	
1	46.5730	22.6430	0.6553	0.3797	0.1584	3.5710	39.8521	a_6		3.2335	
1	46.9668	20.2409	0.5853	0.3407	0.1417	3.1919	44.5895	a_7		3.6268	

			X^{-1}						X^{-1} Y	
-534.4352	125.6753	10.6771	-60.5597	-1.5221	39.1359	222.2879	199.7409		15.6264	a_0
2.6675	-0.1224	-0.0372	0.6141	0.0091	-0.2290	-1.6377	-1.2643		0.0409	a_1
0.3007425	-0.03493	0.01904	-1.21989	-2.1872	0.97485	2.249002	-0.10164		-0.0533	a_2
54.354732	20.39166	-111.23	5407.147	43.3409	-1298.5	-4100.93	-14.5427		78.3097	a_3
-1.62947	0.855524	-130.25	90.12323	2.27788	-19.942	57.81747	0.750331	=	-1.1412	a_4
-124.48	13.65389	197.417	-4898.83	-54.071	3022.85	1817.153	26.30735		-33.2464	a_5
55.751281	-22.0323	23.9191	-775.238	8.20644	96.9224	633.093	-20.6215		-15.0695	a_6
4.7430483	-1.41414	-0.0931	0.662726	0.01549	-0.426	-1.98649	-1.50151		-0.1228	a_7

APPENDIX A9

Matrices of Resistance Group 1 Non linear multiple regression analysis Matrix (A.22) is gotten by dividing Equations (4.71a) to (4.71h) by 6, 10.008, 7.9073, -1.327, -2.7354, -5.0221, 3.0945 and 9.6731 respectively.

X										Y	
1.0000	1.6680	1.3179	-0.2211	-0.4559	-0.8370	0.5158	1.6122	a_0		0.5623	
1.0000	1.6715	1.3161	-0.2230	-0.4576	-0.8388	0.5132	1.6132	a_1		0.5653	
1.0000	1.6657	1.3268	-0.2120	-0.4473	-0.8281	0.5247	1.6037	a_2		0.5551	
1.0000	1.6818	1.2637	-0.2762	-0.5081	-0.8911	0.4616	1.6632	a_3	=	0.6057	[A.22]
1.0000	1.6742	1.2930	-0.2464	-0.4799	-0.8619	0.4908	1.6358	a_4		0.5822	
1.0000	1.6717	1.3038	-0.2354	-0.4694	-0.8511	0.5017	1.6254	a_5		0.5736	
1.0000	1.6622	1.3408	-0.1979	-0.4338	-0.8142	0.5387	1.5905	a_6		0.5487	
1.0000	1.6690	1.3109	-0.2281	-0.4626	-0.8439	0.5088	1.6195	a_7		0.5677	

X^{-1}									$X^{-1}Y$	
-50562.56	1741.99	36535.27	21635.58	-21956.9	-9117.93	10906.07	10819.49		51.8463	a_0
5141.84	92.85	-2901.27	-1401.64	-742.81	2087.07	-1838.84	-437.20		-8.2144	a_1
9645.39	-265.02	-9742.44	-4960.81	12120.19	-4483.02	1362.45	-3676.75		6.2016	a_2
5602.84	-575.77	2965.66	-7338.56	4606.20	7208.85	-9903.88	-2565.32		-47.6102	a_3
-16702.13	530.52	1262.60	3398.66	-4244.12	4889.42	7131.86	3733.20	=	33.9609	a_4
-7730.50	1222.47	7614.78	9854.42	-9779.77	-10729.75	4701.38	4846.96		22.8942	a_5
14893.62	-842.67	-7220.98	-2874.21	-3258.68	5698.95	-4635.13	-1760.92		-22.1983	a_6
5425.53	15.40	-4668.72	-1924.23	-123.18	2138.39	-1393.71	530.52		-6.3186	a_7

APPENDIX A10

Matrices of Resistance Group 2 Linear Multiple Regression Analysis

Matrix (A.23) is gotten by dividing Equations (4.73a) to (4.73h) by 6, 283.7, 207.6, 0.66, 0.36, 1.5, 23.22 and 477.6 respectively.

X										Y	
1.0000	47.2833	34.6000	0.1100	0.0600	0.2500	3.8700	79.6000	a_0		1.2833	
1.0000	47.4656	34.8290	0.1106	0.0605	0.2517	3.8950	79.3550	a_1		1.2760	
1.0000	47.5963	35.9441	0.1136	0.0622	0.2604	4.0197	78.8150	a_2		1.2433	
1.0000	47.5606	35.7273	0.1136	0.0621	0.2591	3.9955	78.5303	a_3	=	1.2409	[A.23]
1.0000	47.6389	35.8889	0.1139	0.0611	0.2611	4.0139	78.9444	a_4		1.2444	
1.0000	47.6133	36.0400	0.1140	0.0627	0.2613	4.0300	78.9333	a_5		1.2453	
1.0000	47.5883	35.9388	0.1136	0.0622	0.2603	4.0189	78.8114	a_6		1.2433	
1.0000	47.1378	34.2588	0.1085	0.0595	0.2479	3.8317	80.7873	a_7		1.3220	

X^{-1}									$X^{-1}Y$	
-403.12	-127.63	-501.37	574.74	-142.90	-892.69	1190.49	303.49		1.5074	a_0
-0.38	5.72	12.12	-4.50	1.32	6.02	-17.75	-2.54		-0.0042	a_1
-97.23	37.84	-454.38	44.48	-1.54	-75.85	506.35	40.34		0.2623	a_2
4171.97	-1056.79	-3038.52	-2286.98	886.93	5090.70	-1699.40	-2067.92		-13.777	a_3
-686.89	217.11	2510.99	829.43	-635.90	363.22	-2946.19	348.23	=	5.0661	a_4
-2862.73	501.98	768.56	2304.25	-168.79	-2664.25	614.41	1506.58		9.4290	a_5
991.96	-367.73	4043.38	-523.64	14.77	752.45	-4487.18	-424.01		-2.9381	a_6
3.09	-0.64	-0.08	-3.12	0.75	5.08	-3.71	-1.36		0.0141	a_7

APPENDIX A11

Matrices of Resistance Group 2 Non linear Multiple Regression Analysis

Matrix (A.24) is gotten by dividing Equations (4.75a) to (4.75h) by 6, 10.0439, 9.1858, -4.5916, -7.3766, -3.6678, 3.4778and 11.3862 respectively.

X										Y	
1.0000	1.6740	1.5310	-0.7653	-1.2294	-0.6113	0.5796	1.8977	a_0		0.1008	
1.0000	1.6744	1.5317	-0.7646	-1.2286	-0.6105	0.5804	1.8973	a_1		0.1002	
1.0000	1.6748	1.5355	-0.7600	-1.2252	-0.6065	0.5841	1.8964	a_2		0.0977	
1.0000	1.6726	1.5203	-0.8735	-1.2405	-0.6252	0.5691	1.8854	a_3	=	0.0805	[A.24]
1.0000	1.6728	1.5257	-0.7722	-1.2347	-0.6169	0.5744	1.8990	a_4		0.1045	
1.0000	1.6718	1.5190	-0.7827	-1.2407	-0.5987	0.5677	1.9006	a_5		0.1081	
1.0000	1.6761	1.5429	-0.7514	-1.2183	-0.5987	0.5915	1.8943	a_6		0.0926	
1.0000	1.6737	1.5299	-0.7603	-1.2303	-0.6122	0.5786	1.8992	a_7		0.1030	

X^{-1}									$X^{-1}Y$	
-343365	-16148.8	537664	2205.5	-6850.1	-698.2	-201606.8	28800.1		-12.0255	a_0
56580.2	5081.8	-90595.0	-402.1	829.2	128.1	33612.7	-5235.0		2.2839	a_1
70387.4	-369.9	-96626.5	-632.6	538.4	123.7	35606.5	-9026.9		2.7471	a_2
-5547.0	-112.6	8882.6	-1.1	51.0	-13.1	-3336.7	76.9		0.2314	a_3
-54455.6	-3377.1	88805.1	436.7	-2935.6	-128.5	-33912.9	5568.0	=	-3.0253	a_4
21.5	-0.9	-87.8	-2.8	-11.8	39.6	63.5	-21.4		0.0054	a_5
-11689.7	3084.3	1016.6	272.3	1992.2	-27.9	945.4	4406.9		-1.1115	a_6
40303.2	1149.8	-64678.9	-98.7	-49.7	87.9	24276.9	-990.6		0.6336	a_7

APPENDIX B1

Plate B1 – Nguzu Edda Erosion Site 1

APPENDIX B2

Plate B2- Researcher in Nguzu Edda Erosion Site 2

APPENDIX B3

Plate B3- Access Road to Nguzu Edda Erosion Site 2

APPENDIX B4

Plate B4 - Lateral Uprooting Test at Nguzu Edda Erosion Site 2

APPENDIX B5

Plate B5 - An uprooted Plant (*M. indica*) in Nguzu Edda Erosion Site 2.