

# Growth potential of various plant species for vegetative rehabilitation of different mine tailings

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It all starts here <sup>™</sup>

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## **Disclaimer**

Any opinion, findings and conclusions or recommendations expressed in this material are those of the author(s) and therefore the NRF/THRIP, Geology Department of the North-West University and Fraser Alexander Tailings do not accept any liability in regard thereto.

## **Abstract**

Vegetation establishment is one of the major rehabilitation methods that are used to stabilize, cover, to minimize, mitigate or remove the contaminants from tailings storage facilities (TSF's). Phytostabilization is a useful mechanism by which plants limit the contamination of natural systems with toxic elements. For successful occurrence of phytostabilization on mine tailings, it is vital to establish plant species that can survive the hostile conditions of the substrate. Major problems encountered with vegetation covers is the lack of natural soil properties e.g. soil structure, organic carbon and also hostile chemical conditions. Only a few species are tolerant to the different negative properties of the tailings.

The main aim of this project is to identify plant species that can be used for vegetative rehabilitation of nine different types of tailings material including gypsum, gold, platinum, kimberlite, coal, fluorspar and andalusite tailings. The ability of 28 different plant species to survive in the tailings was assessed by statistically calculating the growth potential of the species and summarizing the data in graphs and an index table that calculates a specific merit value for each of the tailings-species combinations. The various plant stress factors that the species exhibited were also documented. Finally, the results were correlated with a soil physical and -chemical baseline study of the tailings to provide insight into successes and failures of certain species.

The final results identified various successful tailings-species combinations, as well as failures. The index table proved to be a useful tool to identify suitable species for establishment on various tailings. The baseline study of the different tailings could be used to explain why certain species could be established successfully, as well as the reason why some species did not survive.

**Keywords: tailings storage facility; tailings; phytostabilization; toxic elements; growth potential; index table; baseline study; plant stress factors.**

## **Uittreksel**

Die vestiging van plantegroei is een van die hoof metodes wat gebruik word om die impak van kontaminante op slikdamme te verminder en te stabiliseer. Phytostabilisering is 'n doeltreffende meganisme waarvolgens plante die kontaminasie van natuurlike stelsels met skadelike elemente verminder. Vir phytostabilisering om suksesvol te wees, is dit noodsaaklik om plant spesies wat kan oorleef ten spyte van die ongunstige eienskappe van die mynslik te identifiseer. Die moeilikste hindernisse is die afwesigheid van natuurlike grond-eienskappe, asook die ongustige organiese koolstof en struktuur van die mynslik. Slegs 'n paar plant spesies kan die negatiewe eienskappe van die mynslik oorkom.

Die hoofdoel van die projek is om plant spesies te identifiseer wat vir rehabilitasie van nege verskillende tipes mynslik gebruik kan word, nl. gips, goud, platinum, kimberliet, steenkool, fluorspar en andalusiet mynslik. Die vermoë van 28 verskillende plant spesies om te oorleef in die mynslik was geassesseer deur die groei potensiaal van die spesies stasies te bereken en die data in grafieke en 'n indeks tabel op te som. Die indeks table se funksie is om 'n meriete getal aan elke spesie-mynslik kombinasie toe te voeg. Die verskeie plant stresfaktore deur die verskillende spesies getoon, is ook gedokumenteer. 'n Basisstudie van die grond fisiese en -chemiese eienskappe van die verskillende tipes mynslik is ook gedoen, met die doel om as moontlike verduideliking van suksesvolle en mislukte mynslik-spesie kombinasies te dien.

Die finale resultate het verskeie suksesvolle, sowel as mislukte mynslik-plantspesie kombinasies opgelewer. Die indeks tabel is bewys as 'n bruikbare middle om suksesvolle spesies aan te wys vir vestiging op die verskillende sliktipes. Die basisstudie van die verskillende sliktipes kon gebruik word om suksesse en mislukkings te verduidelik.

**Sleutelwoorde: Slikdamme; mynslik; phytostabilisering; elemente; groei potensiaal; indeks tabel; basisstudie; plant stresfaktore**

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- The chemical analyses in Table 10 to 12 were done by GEOLAB
- For supplying the tailings:

T1	OMV Crushers- Potchefstroom
T2, T3	Mine Waste Solutions- Stilfontein
T4	Anglo Platinum- Rustenburg
T5	Petra Diamonds- Cullinan
T6, T9	Anglo Coal Landau Collieries
T7	Witkop Fluorspar- Zeerust
T8	Bosveld Andalusiet- Groot Marico

- Industrial partner: Fraser Alexander Tailings
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## List of acronyms

AMD:	Acid mine drainage
NAP:	Net Acid Potential
BIC:	Bushveld Igneous Complex
CEC:	Cation exchange capacity
EC:	Electrical conductivity
ESP:	Exchangeable Sodium Percentage
FC:	Field Capacity
PR:	(Root) penetration resistance
PWP:	Permanent Wilting Point
SOM:	Soil Organic Matter
STDV/ $\sigma$ :	Standard deviation
TSF:	Tailings storage facility
UG2:	Upper Group no. 2 reef
FI:	Fluorescence Intensity
PI <sub>ABS</sub> :	Vitality Index

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# Chapter 1 - Introduction

## 1.1 Justification

Due to the wide variety of different mines in South Africa, numerous tailings storage facilities (TSF), occur throughout the country. These TSF's contain pollutants e.g. toxic elements, which can prove hazardous to animals and humans and have a negative impact on ecosystems. The potential hazard of the tailings material to be liberated and transported via wind and water erosion makes sustainable rehabilitation a necessity. The first goal that must be reached for sustainable rehabilitation is surface stability. Using plant species that have been proven suitable for rehabilitation is therefore crucial. Suitability of a species for rehabilitation is determined by the ability to survive, as well as contributing to phytostabilization of the tailings material (Lange *et al.*, 2012).

In South Africa, vegetation has always been the most popular cover option for TSF rehabilitation. Although more and more cover options are proposed and applied, vegetation is still widely used as a secondary cover option, or as a means to alter the water balance. Vegetation also improves on the aesthetics of a TSF (Van Deventer, 2013).

According to Van Deventer (2013), the main functionality of vegetation is visible on tailings storage facilities with regards to the following characteristics:

- Because vegetation acts as a windbreak, it can decrease or even stop dust pollution completely. Plants take up a lot of water through their roots and they act as a physical barrier, decreasing water run-off down steep slopes and therefore erosion and soil loss. Where there is too much water in the soil next to slimes dams, vegetation can also be utilized to lower the water table by means of water uptake through the roots of the plants. Vegetation can improve on the soil structure and soil stability through the roots forming stable soil aggregates. Some plants can absorb toxic heavy metals and store it in their wood cells. It is important to note that the metals remain in the plant rests and care must be taken to prevent consumption by animals or humans.
- Vegetation forms an important part of the ecology and will therefore speed up the recovery of the other parts of the local ecosystem for example the promotion of bird life and small animal species. Vegetation creates a microclimate for various microbes which in turn increases the concentration of a number of enzymes through its digestive activities. Plants are also aesthetically pleasing and look more acceptable. It is thus critical to have knowledge of specific species that have proven successful for rehabilitation of TSF's, as early as in the planning phase of a rehabilitation project (Van Deventer, 2013).

## 1.2 Objectives of study

The main aim of this project is to identify plant species that can be used for vegetative rehabilitation of nine different types of tailings material including gypsum, gold (two types), platinum, kimberlite, coal, fluor spar and andalusite tailings. The ability of 28 different plant species to survive in the tailings will be assessed by statistically calculating the growth

potential of the species and summarizing the data in graphs and an index table that calculates a specific merit value for each of the tailings-species combinations.

The various plant stress factors that the species exhibited were also documented. Finally, the results will be correlated with a soil physical and soil chemical baseline study of the tailings to provide insight into successes and failures of certain species.

## Chapter 2 - Literature review

### 2.1 Phytostabilization and the significance of vegetation as a cover option

The United States Environmental Protection Agency (2012) defines phytoremediation as the in situ use of vegetation, and the microorganisms associated with it, to stabilize or reduce contamination in soils, sludges, sediments, surface water, or ground water. According to Jadia & Fulekar (2009:924-926) there are several recent techniques to phytoremediate contaminated soils. These include phyto-extraction, phytostabilization, rhizofiltration and phytovolatilization.

According to Van Deventer (2014), phytostabilization refers to the physical stabilization of any surface, i.e. side slopes of TSF's, by plants. Mendez & Maier (2008:278), supports this by stating specifically that phytostabilization is the *in situ* stabilization of the tailings material by using plants.

Vegetative material increases soil cover (cover [C-] factor in the USLE and RUSL soil erosion equation) and consequently decreases soil erosion and the mobilization of any contaminants, e.g. trace elements and harmful salts. Leaching of contaminants is also reduced due to the hydraulic control exercised by plant roots, and the addition of soil organic matter by plants decreases the solubility of trace elements in a growth medium (Van Deventer, 2014).

On a microscopic scale plants also have a stabilizing effect on the contaminants in mine tailings. Cunningham *et al.* (1995 [cited by Mendez & Maier, 2008:279]) states that in theory, metal toxicity will decrease as plants cause metals to precipitate to forms that are less bio-available/soluble, adsorb metals on to root surfaces or accumulate metals into root tissues. According to Glick (2003:384) the stimulation of microbial biodegradation can also occur.

Another advantage of phytostabilization is that harvested biomass does not need to be disposed, because the main principle of phytostabilization is to immobilize the contaminants in the soil, as opposed to absorbing it into plant tissues. It is also a remediation option that can be implemented quickly (Slabbert, 2014).

### 2.2 Soil physical quality indicators

#### 2.2.1 Soil texture and particle size distribution

Soil texture is defined as the particle size range of a soil expressed in fractions (by mass) of sand, silt and clay (Hillel, 2004:439).

Soil texture is an important soil physical quality indicator that drives plant production and field management of soils. The textural class of a soil is determined by assessing the percentages of sand, silt and clay that it is comprised of. The four major textural classes into which soils or a growth medium can be divided are: sands, silts, loams and clays. The nomenclature used when addressing soil textures dictates that a clay soil is fine textured and a sandy soil is coarse textured. The properties of the growth medium affected by texture include drainage, water holding capacity, water retention, aeration, susceptibility to erosion, organic matter content, pH buffering capacity and tilth (Berry *et al.*, 2007:1).

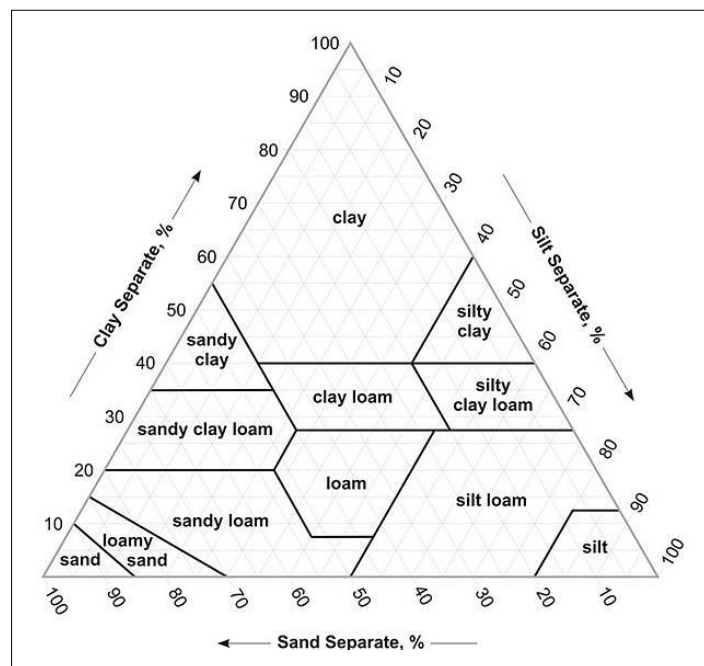
Tilth is a term used to describe the quality of the structure of a soil or growth medium and is a term that predates modern agriculture (Kay & Grant, 1996:37).

Soil texture greatly affects the hydrological characteristics of a soil or tailings. Texture determines the rate at which water drains through a saturated growth medium. Water will move more freely through a sandy soil than through clay. Plant available water is also affected by the texture because clay retains more water due to capillary forces and adsorption. In addition, well drained soils are typically more aerated which is essential for healthy root development and therefore a healthy plant or crop (Berry *et al.*, 2007:1).

The susceptibility to erosion of a growth medium is also greatly influenced by the texture. A soil with a high percentage silt or clay is more susceptible to erosion than coarse sand. The sand is less weathered relative to the clay and therefore requires more energy for erosion to take place (Berry *et al.*, 2007:1).

Due to the better aeration of sandy soils, the rate of the breakdown of organic matter is typically faster than for a clay rich medium. Oxygen is more readily available for the breakdown processes of the organic material (Berry *et al.*; 2007:1). The influence of the soil texture on the CEC and the pH of the growth medium will be further explained under 3.6.1 pH (H<sub>2</sub>O) and 3.6.2 pH (KCl).

The USDA soil classification method is most commonly used to put soils into texture classes if the different size fractions of the soil is known. Figure 1 can be used to class the soil (United States Department of Agriculture, 2013).



**Figure 1: USDA soil texture classification pyramid**

The method used to determine the percentages of the different particle size fractions is described in 3.5.1 *Particle size distribution*. The different size fractions as defined by Wentworth (1922) in Table 1.

**Table 1: The canonical definition of sediment grain sizes**

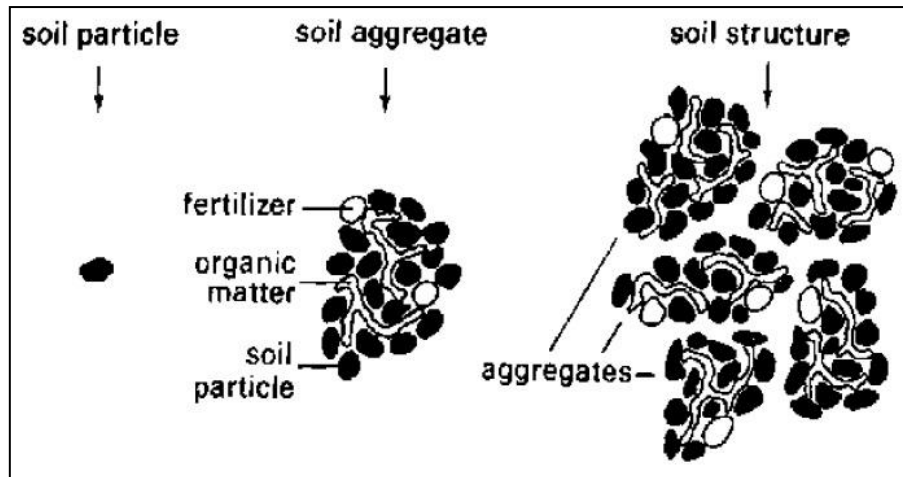
Millimeters (mm)	Micrometers ( $\mu\text{m}$ )	Phi ( $\phi$ )	Wentworth size class
4096		-12.0	Boulder
256		-8.0	Gravel
64		-6.0	
4		-2.0	
2.00		-1.0	
1.00		0.0	Very coarse sand
1/2	0.50	1.0	Coarse sand
1/4	0.25	2.0	Medium sand
1/8	0.125	3.0	Fine sand
1/16	0.0625	4.0	Very fine sand
1/32	0.031	5.0	Coarse silt
1/64	0.0156	6.0	Medium silt
1/128	0.0078	7.0	Fine silt
1/256	0.0039	8.0	Very fine silt
	0.00006	14.0	Clay

### 2.2.2 Soil structure

Soil structure refers to the configuration of the soil matrix i.e. the arrangement and organization of the particles in a soil and can be single grained and individually stacked or aggregated (Hillel, 2004:439).

Soil structure also refers to the natural aggregation of the primary soil particles in units or peds that are divided according to levels of weakness. The cohesion that exists between peds is stronger than the adhesion between them. There are four major structure classes: cubic, spheroidal, prismatic and plate structures. Four different terms can be used to describe the degree of aggregation: structureless or intact (no apparent aggregation and no natural sorting of weak structure units); weak (peds are weakly developed and cannot be identified clearly); medium structured (peds are well formed and stable but not well separated in undisturbed soil) and strong (peds are well formed and stable as well as separated in undisturbed soil). The term apedal is used where a medium is well aggregated but peds cannot be observed on a macroscopic level. (Soil Classification Working Group; 1991:247-248) The formation of soil aggregates and soil structure is illustrated in Figure 2 (Joseph, 2010:14).

Soil structure influences the ability of a growth medium to support plant roots and root development, to receive, store and transmit water and energy, to cycle carbon and nutrients and to resist soil erosion and dispersion of chemicals (Kay & Grant, 1996:37).



**Figure 2: Formation of soil aggregates and structure.**

The main factors influencing the structure of a growth medium are texture, clay mineralogy, composition of exchangeable ions and organic carbon content. Other factors that may or may not influence the structure are management practices (e.g. tillage, traffic and irrigation), weather (e.g. frequency and intensity of rainfall events and freeze/thaw events) and biological events (e.g. earthworm burrowing, microbial activity as well as root growth and development). (Kay & Grant, 1996:38)

Vegetation establishment is therefore very beneficial for the structure of the tailings dam, as it stabilizes the material by binding it to the roots and via hydraulic control of the soil water. Vegetation also acts as an ecosystem for microbial communities, while dead plant matter increases the soil organic matter, all of which aids in improving structure (Van Deventer, 2014).

### **2.2.3 Compaction, Hardsetting and Crusting**

Compaction is when dry soil densifies by reduction of fractional air volume (Hillel, 2004:429).

The degree to which a soil is compacted is an important structural characteristic and soil quality indicator. The plant growth factors that are most frequently identified as the most critical in severely compacted soils are aeration and penetration resistance (Håkkanson & Lipiec, 2000:71).

Håkkanson and Lipiec (2000:74-75) states that several reports in literature indicate that an air filled porosity of 10% and a penetration resistance of 3000 kPa often represent critical limits of soil aeration and root development. However, according to Taylor *et al.*, as well as Benjamin *et al.* (as cited by Reichert, da Silva and Reinert, 2004) the maximum value of 2000 kPa is widely accepted as critical for root growth (Reichert *et al.*, 2004:1).

If a growth medium is too hard, root development cannot take place. This hardness is most commonly expressed in terms of penetration resistance and is measured with a penetrometer at field capacity.

Soil chemical hardsetting is strongly affected by clay mineralogy and texture. Soil hardness can also affect shoot growth. A possible explanation for this phenomenon is the inability of the hampered roots to supply the shoots with adequate water and nutrients. (Passioura, 2002:311)

#### 2.2.4 Bulk density

The dry bulk density ( $\rho_b$ ) expresses the ratio of the mass of solids to the total soil volume i.e. the solids and the pores (Hillel, 2004:13).

In a study conducted by Mirreh & Ketcheson (1972), penetrometer resistance values for different soil treatment combinations indicated that resistance to root penetration increases with increasing bulk density and moisture retention (Mirreh & Ketcheson, 1972:479).

A general scale of bulk density is given by Table 2 (Hazelton & Murphy, 2007:20).

**Table 2: General scale of bulk density values**

Bulk density ( $\text{g.cm}^3$ )	Rating
<1	Very low
1 – 1.3	Low
1.3 – 1.6	Moderate
1.6 – 1.9	High
>1.9	Very high

The dry bulk density should not be confused with particle density ( $\rho_s$ ), which is the ratio of the mass of the solids to the volume of the solids. Bulk density will always be smaller than  $\rho_s$ , and where the mean particle density usually remains constant, the bulk density is labile. Bulk density can be affected by the structure of the growth medium, whether it is loose or compacted as well as swelling and shrinking characteristics of the medium. The latter is a function of both clay mineralogy and water content. Even in extremely compacted soils, the bulk density can never be as high as the density of the solids because the particles can never interlock perfectly. A large fraction of the pore space can be eliminated through compaction; it can never be entirely eliminated (Hillel, 2004:13).

Bulk density can be used as an indicator explaining difficulty in establishment of vegetation. Root development may be negatively affected due to compaction of soil.

Bulk density is a good indicator of the porosity of the growth medium. Coarse grained material will have mostly macropores due to the loose arrangements between particles. Fine textured soils typically have more micropores because they are more tightly arranged and therefore have a greater porosity. Porosity can be subdivided into aeration porosity and capillary porosity. Aeration porosity is the percentage of pore space filled with air after the soil has been left to drain water freely, that is until field capacity is reached. Capillary porosity is the percentage of pore space that may be filled with capillary water. Porosity is largely dependent on the structure and texture of the soil. Sandy and organic soils typically have a high aeration porosity where that of clay is low. Clay has a high capillary porosity. Aeration porosity influences plant growth, density and permeability (Joseph, 2010:14).

## 2.2.5 Water holding capacity, Field capacity and Plant available water

Successful vegetation establishment is dependent on two natural resources, soil (growth medium) and water. Soil provides plants with nutrients as well as mechanical support and stability, while water is essential for nutrient uptake into plant roots as well as other plant life-processes. Effective vegetation establishment requires an understanding of the relationship between the soil, water and plants (Joseph, 2010:12).

The spaces that exist between soil particles, called pores, provide the pathways for air and gas to move in soil and for the retention of water by a soil or growth medium. Texture, specifically particle size, plays a fundamental role in the ability of a soil to retain and store water. Clay type, organic content and soil structure also influences the water holding capacity of a soil (Joseph, 2010:16).

Capillary rise in soil pores occurs as a result of surface tension and adhesion. Surface tension is the phenomenon by which water molecules are bound in two dimensions at the surface of a water body, instead of the normal H-O-H three dimensional configurations. This increases the bond strength along the surface, creating a layer of increased molecular attraction. If the soil pores are compared with a thin tube, water attempts to cover the entire tube wall through adhesion. However, surface tension in the molecular layer cannot exceed the weight and internal cohesion of the water. As the adhesive forces between the water molecules adjacent to the pore walls draw the water upward, the surface tension drags the surface film upward as well, raising the entire water body against the forces of gravity (Winegardener, 1995:71-73). This explains why a clay-rich medium has a greater ability to retain water. The effect of the smaller particle fraction is that the pores in the material are essentially narrower and tight, causing adhesion to be much greater and therefore water is held effectively against the forces of gravity.

The phenomenon of hygroscopic water can also explain why clay-rich soils retain water well. Hygroscopic water is absorbed from the air/atmosphere to particle surfaces. Strong adhesion forces bind water molecules to particle surfaces. A hygroscopic water layer consists of an extremely well arranged monomolecular layer around a negatively charged soil particle (Saarenketo, 1998:74).

The mineralogy of a material can also affect its water holding capacity. Some mineral compounds have a greater attraction to water molecules than others. This attraction can be either to the oxygen or hydrogen in the water molecule. An example of one of the hydrophilic compounds, perhaps the most common one, is the many varieties of silicate minerals. The basic silicate structure is that of the silica tetrahedral or octahedron of silicon dioxide ( $\text{SiO}_2$ ). The oxygen in the silica molecule presents the opportunity for hydrogen bonding to occur. This can be compared to raindrops sticking to a glass window pane. Only when the drops become heavy enough can the adhesion force between the water molecules and the glass be overcome and will the water start sliding to the bottom (Winegardener, 1995:72).

The percentage of water remaining in a soil two to three days after having been saturated and after free drainage has ceased, is called the field capacity (Winegardener, 1995:236).

The permanent wilting point is the soil condition at which the plant undergoes a permanent reduction in its water content because of a deficient supply of water, a condition from which the leaves do not recover in a saturated atmosphere overnight. The permanent wilting point

is influenced by the characteristics of the plant and meteorological conditions. These two concepts are important to understand, as they are the two constraints that exist in the definition of plant available water. The plant available water is the amount of water held by a soil between field capacity and permanent wilting point. Water is too strongly bound to the soil particles when the water content drops below PWP and is therefore not available for plant root uptake. Above FC, water either drains away before plant root uptake or aeration problems restrict the uptake process (Joseph, 2010:19).

### 2.2.6 Water infiltration capacity (Infiltrability)

The infiltrability of a soil can be defined as the resulting infiltration flux when water at atmospheric pressure is made available to the surface of the soil (Hillel, 2004:260).

Soil infiltrability and its variation with time are known to depend on the initial wetness, suction, texture, structure and profile uniformity. During the early stages of precipitation infiltrating into a soil, the infiltrability is relatively high especially if the soil is very dry. The infiltrability then starts to decrease to a constant rate that is termed the steady-rate infiltrability. The decrease of initial infiltrability can in some cases be attributed to the degradation of the structure of the soil as well as partial sealing of the surface by means of a crust. Other reasons for a decline in infiltrability include the detachment and migration of pore-blocking particles, the swelling of clay, as well as the entrapment of air bubbles or if the air originally present in the soil cannot escape due to bulk compression by the infiltrating water. Though the aforementioned reasons can be responsible for the decline in infiltrability, the main reason is usually a decrease in the matric suction gradient, which occurs inevitably as infiltration proceeds. When the surface of a dry soil is suddenly wetted, there exists a large difference in the hydraulic potential between the saturated surface and the deeper dry soil. This causes suction and a very high initial infiltration rate, which declines as the deeper laying soil becomes more saturated with water (Hillel, 2004:261-262).

Basic infiltration rates for various soil types are given by Table 3 (FAO, 2014).

**Table 3: Basic infiltration rates for various soil types**

Soil type	Basic infiltration rate (mm/h)
Sand	Less than 30
Sandy loam	20 - 30
Loam	10 - 20
Clay loam	5 - 10
Clay	1 - 5

## 2.3 Soil chemical quality indicators

### 2.3.1 Soil pH

pH is viewed by many as the master variable of soils because it affects numerous processes that occur in soil, as well as various soil characteristics. Soil pH has a significant effect on the availability of plant nutrients and microorganisms. At low pH levels heavy metals such as Al, Fe and Mn become soluble and available for plant root uptake, causing toxicity in plants. On the other hand, if the pH increases, the solubility of these metals will start to decrease and precipitation will start to occur. Plants will start to experience growth deficiencies when the pH of the soil rises above 7. (Sparks, 2003:267)

One of the major problems when plants are grown in an acidic medium is aluminium toxicity. Aluminium in the soil causes stunted roots (rhizotoxicity) and tops in plants. The degree of toxicity and the exact effect on the plant depends on the plant- and aluminium species. For example, studies have shown that polymeric Al species in an aqueous solution was five to ten times more rhizotoxic to wheat than  $Al^{3+}$ . (Sparks, 2003:268)

Acidity can have a dramatic effect on the soil environment. Examples of this include the effects of acid rain on soils, or the presence of mine spoils and Acid Mine Drainage (AMD) (Sparks, 2003:268). For the purposes of this study, only acidification as a result of mining spoils and AMD will be investigated.

### 2.3.2 Acid mine drainage

Acid Mine Drainage (AMD) has been found to be the main cause where acidity problems occur in the tailings materials, especially at gold and coal mines. When acidic potential is being assessed, it is important to note the different influences that cause acidity:

- Active acidity occurs due to  $H^+$  ions (protons), which are in solution in the soil water.
- Potential acidity is due to  $H^+$  ions (protons), which occur on the exchange complexes of mineral grains of the clay particles.

To measure the acidity of tailings material more accurately, it is important to factor in the active and potential acidity. This is done by preparing samples with a KCl and  $H_2O$ . The potassium exchanges with the  $H^+$  ions on the exchange complexes, therefore bringing them into solution as well. The pH that is then measured will be the sum of the  $H^+$  ions in solution as well as on the exchange complexes. Along with pH or  $H^+$  ion concentrations, laboratories usually determine net acid potential (NAP) for a soil or tailings material, that is the capacity of the material to produce acid. This is important to know in order to determine liming requirements.

- Residual acidity relates specifically to the AMD potential because this describes the oxidation of a sulphur rich mineral, commonly pyrite. This contributes to the ongoing acidity potential of a TSF. It is therefore possible to assess the ongoing acidification potential of a TSF by analysing the total S concentration.

- Another contributor to the acidity of a TSF is latent acidity, which occurs through hydrolysis, protonization and oxidation (Johnson & Hallberg, 2005:1).

Acidic sulphur-rich wastewater is caused by a variety of industrial processes, chief of which is the mining industry. Water draining from mines and mine wastes are often extremely net-acidic (Johnson & Hallberg, 2005:1).

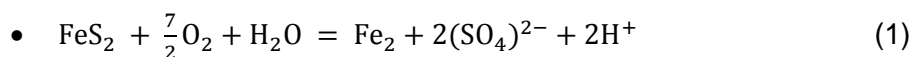
Briefly explained, acidic metal-rich mine drainage waters are caused by the oxidation of sulphidic minerals, mainly pyrite ( $\text{FeS}_2$ ). This process is accelerated by the exposure of these minerals to water and oxygen during mining and processing of metal-ores (Johnson & Hallberg, 2005:1-2).

The following reactions (INAP, 2009) can take place and cause AMD on a gold TSF:

- i.  $\text{FeS}_2 + \frac{7}{2}\text{O}_2 + \text{H}_2\text{O} = \text{FeSO}_4 + \mathbf{H}_2\mathbf{SO}_4$
- ii.  $\text{FeSO}_4 + \frac{1}{4}\text{O}_2 + 1.5\text{H}_2\text{O} = \text{FeOOH} + \mathbf{H}_2\mathbf{SO}_4$
- iii.  $3\text{FeSO}_4 + \frac{3}{4}\text{O}_2 + \frac{9}{2}\text{H}_2\text{O} + \text{K}^+ = \text{KFe}_3(\text{SO}_4)_2(\text{OH})_6 + \mathbf{H}_2\mathbf{SO}_4 + \mathbf{H}^+$
- iv.  $\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6 = 3\text{FeOOH} + \frac{1}{2}\text{K}_2\text{SO}_4 + \frac{3}{2}\mathbf{H}_2\mathbf{SO}_4$
- v.  $8\text{FeSO}_4 + 2\text{O}_2 + 10\text{H}_2\text{O} = \text{Fe}_8\text{O}_8(\text{OH})_6\text{SO}_4 + \mathbf{7H}_2\mathbf{SO}_4$
- vi.  $\text{Fe}_8\text{O}_8(\text{OH})_6\text{SO}_4 + 2\text{H}_2\text{O} = 8\text{FeOOH} + \mathbf{H}_2\mathbf{SO}_4$

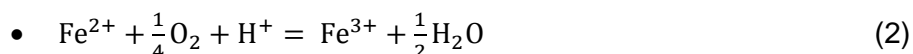
AMD resulting from mine wastes or tailings is often more aggressive than AMD resulting from the mining activities themselves, because of the disaggregated state of the tailing materials. Regarding tailings dams, another important consideration is the long term pollution effect, meaning AMD production may continue for years after decommissioning. (Johnson & Hallberg, 2005:2)

Reaction 1 illustrates the oxidation of pyrite, yielding dissolved ferrous iron, sulphate and hydrogen.

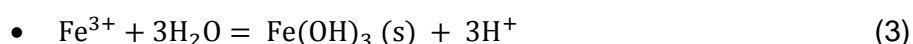


(INAP, 2009)

If sufficiently oxidizing conditions prevail, ferrous iron ( $\text{Fe}^{2+}$ ) may be oxidized to ferric iron ( $\text{Fe}^{3+}$ ). This happens according to the reaction:



Hydrolysis and precipitation of  $\text{Fe}^{3+}$  may also occur, according to the reaction:

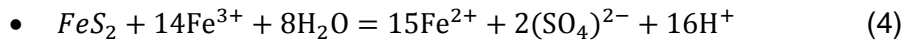


Reactions 2 and 3 dominate at pH levels  $>4.5$ . Declining pH levels will slow down hydrolysis, yielding ferric iron oxidant (reaction 3). Acid production by the ferric iron oxidants become

dominant at low pH levels, where ferric iron ( $\text{Fe}^{2+}$ ) is more soluble (Johnson & Hallberg, 2005:2).

AMD generation is catalysed by the influence of bacteria, specifically *Thiobacillus ferrooxidans* and *Thiobacillus thiooxidans*. (INAP, 2009).

The final reaction will thus be:



(Aucamp, 2000:2.21-2.22)

It is important to note that the pH of acidified waters may be above 6 because of low dissolved oxygen concentrations, especially at the point of discharge. Some waters may remain neutral to alkaline, although some show a distinct pH decline as they oxygenate. This is because the total acidity is the sum of the following factors:

- i. Proton acidity, therefore hydrogen ion concentrations.
- ii. Mineral acidity, therefore the concentrations of ions which produce protons when they hydrolyse.

Acidity is in offset against any alkalinity present, mainly in the form of bicarbonate ( $\text{HCO}_3^-$ ). This alkalinity can be the result of basic minerals such as calcium carbonate ( $\text{CaCO}_3$ ), or by biological processes (Johnson & Hallberg, 2005:2).

### 2.3.3 Soil salinity and Sodicity

According to Jurinak & Suarez (1990) (cited by Sparks, 2003), salinity can be defined as “the concentration of dissolved mineral salts present in water and soils on a unit volume or weight basis”. Salt-affected soils can fall into the categories of either being saline, sodic, or saline-sodic. Saline soils contain high levels of soluble salts, sodic soils contain high levels of exchangeable sodium and saline-sodic salts contain both. Saline soils occur mostly in semi-arid to arid climates because in areas where rainfall is high, salts are leached out of the soil by water from precipitation (Sparks, 2003:285-286).

The important parameters to consider when assessing if a growth medium is saline, sodic or saline-sodic, respectively, are electrical conductivity (EC) and exchangeable sodium percentage (ESP).

The major sources of soluble salts in soils are weathering processes of native rocks, atmospheric deposition, saline irrigation and drainage waters, fossil salts, saline groundwater and seawater intrusions, fertilizers, sewage effluents, brines from natural salt deposits as well as from mines (Suarez & Jurinak, 1990:42-63).

Salinity in a TSF can be due to an arid climate, evapotranspiration, poor drainage, redox reactions of sulphates and where irrigation systems are used for vegetative rehabilitation, poor irrigation water quality (Sparks, 2003:287).

The major cations of concern in saline soils are  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^+$  and the anions  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$  and  $\text{NO}_3^-$ . In hyper-saline waters or brines, B, Sr, Li,  $\text{SiO}_2$ , Rb, F, Mo, Mn, Ba and Al may also be present. When soluble salts accumulate,  $\text{Na}^+$  often acts as the ion acting on the exchange complexes, causing the soil to disperse. This causes soil physical problems like low infiltration and hydraulic conductivity rates, as well as poor internal drainage capacity. The reason for this may be that  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  precipitates as  $\text{CaSO}_4$  (gypsum),  $\text{CaCO}_3$  (calcium carbonate) and  $\text{Ca,Mg}(\text{CO}_3)_2$  (dolomite), causing  $\text{Na}^+$  to replace it on the exchanger phase (Sparks, 2003:287).

EC is the preferred index for measuring soil salinity. EC measurements are easy to do, quick and most important, reliable. EC is based on the concept that the electrical current that a saline solution can conduct, will increase as the concentrations of the salts increase (under normal conditions). EC is measured in milli Siemens per meter ( $\text{mS.m}^{-1}$ ) (Sparks, 2003:290).

According to Greenland & Hayes (1978), as quoted by Harmse & Gerber (1988:411), dispersion is a physical consequence of chemical factors. Clay minerals play an important role to make soils dispersive. The cation exchange capacity (CEC, expressed in  $\text{me100g}^{-1}$  clay) can be used to broadly define categories in which certain minerals in the soil will have related properties. These categories are:

- 2:1 phyllosilicates;  $\text{CEC} = 40 - 15 \text{ me100g}^{-1}$  clay; hydromica, vermiculite, chlorites, smectites; derived from ionic substitution.
- 1:1 phyllosilicates;  $\text{CEC} = 5 - 40 \text{ me100g}^{-1}$  clay; negative charges are pH dependent; arise from broken edges and protonization of *O* and *OH* groups.
- *Fe* and *Al* oxides and hydroxides;  $1 - 5 \text{ me100g}^{-1}$  clay; no dispersion.

(Harmse & Gerber, 1988:413)

ESP can be described by the equations:

- $\text{ESP} = \frac{[\text{Na}^+]}{\text{CEC}} \times 100$
- $\text{ESP} = \frac{[\text{Na}^+]}{[\text{Ca}^{2+} + \text{Mg}^{2+} + \text{K}^+]} \times 100$

(Seilsepour, Rashidi & Khabbaz; 2009:1)

Figure 3 illustrates the procedure suggested by Harmse (1980 [cited by Harmse & Gerber, 1988:415]) to identify the dispersiveness of a soil.

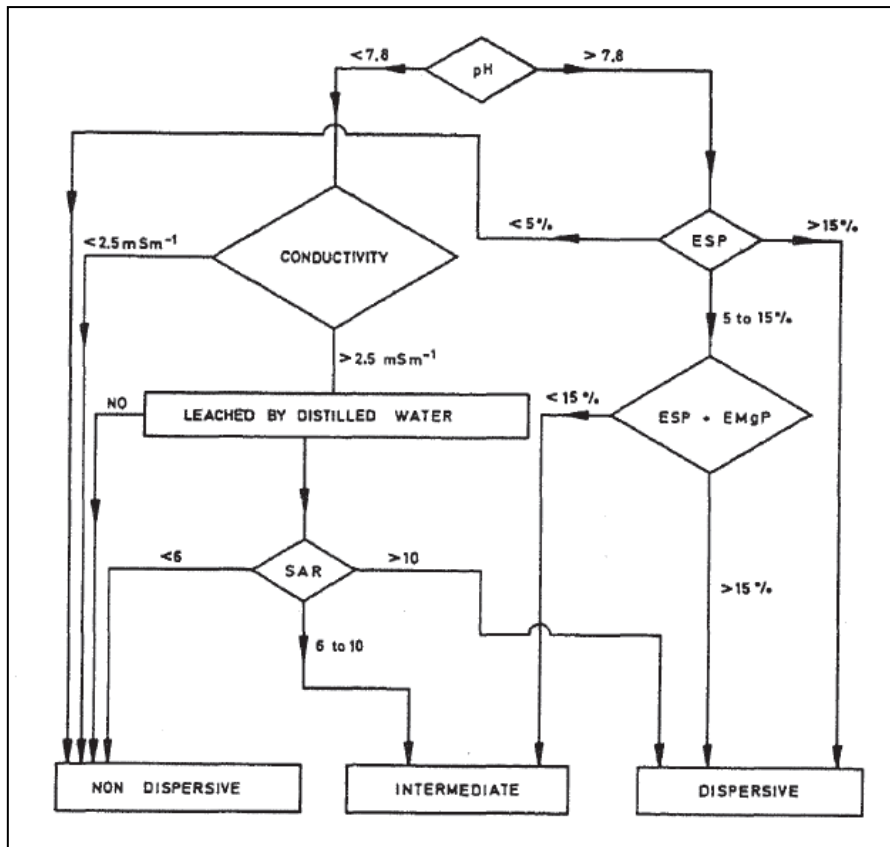


Figure 3: Diagram for identification of dispersive soil from which free salts were not removed

The degree of dispersiveness should then be determined using Figure 4 (Harmse & Gerber, 1988:413).

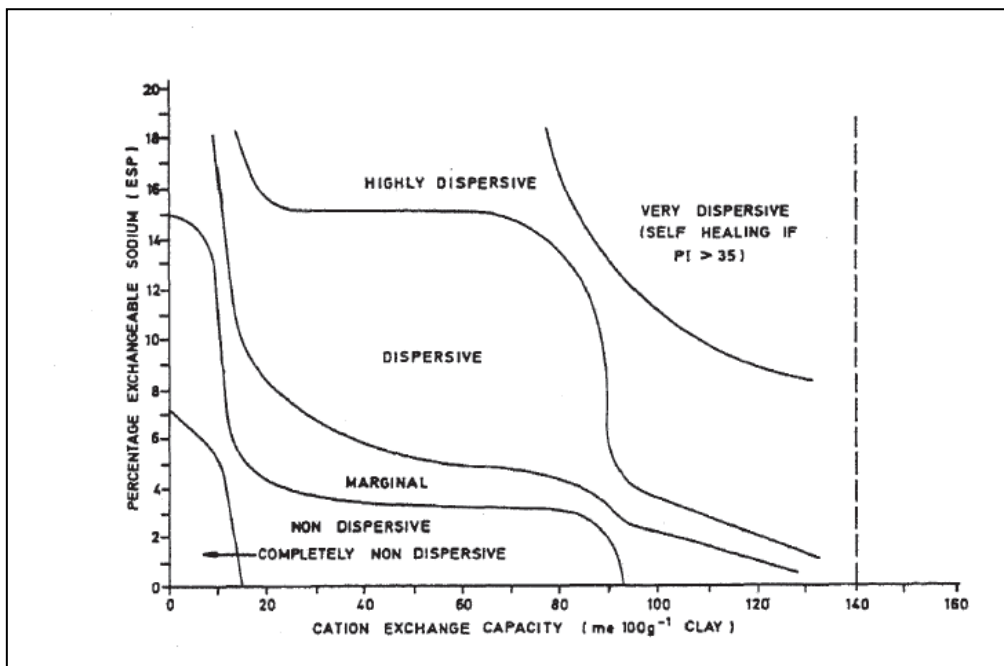


Figure 4: Influence of clay composition (me100g<sup>-1</sup> clay) and ESP on dispersion

Soils with an ESP >30 are very impermeable, and this stunts plant growth. An ESP of >15 is considered a sodic soil, however, the accuracy of this number can present a challenge due to errors that may occur when measuring the CEC or Na<sup>+</sup> concentration. Saline soils are classified as those in which the EC of the saturation extract is >400 mS.m<sup>-1</sup> and ESP <15%. Sodic soils have an ESP >15% and an EC of <400 mS.m<sup>-1</sup>. The high amount of Na<sup>+</sup> in these soils, along with the low EC, results in dispersion. These soils have weak structural stability, low hydraulic characteristics and infiltration rates. Saline-sodic soils have an EC of >400 mS.m<sup>-1</sup> and ESP >15%. As long as the electrolyte concentration remains high, pH will usually be less than 8.5 and the material will remain flocculated. If the salts leach out however, Na<sup>+</sup> becomes a problem as the pH rises to above 8.5, causing the soil/material to disperse (Sparks, 2003:293-295). The effects of sodicity and salinity on plants are summarized by Figure 5 (Läuchli and Epstein, 1990:113-137).

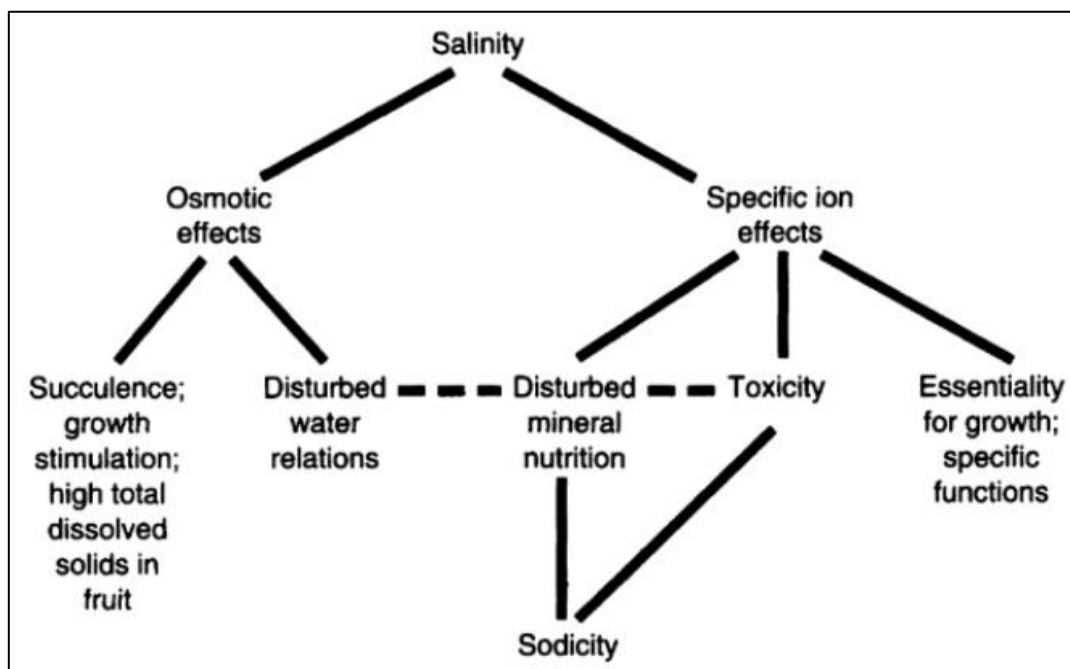


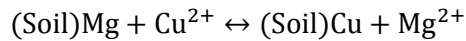
Figure 5: Effects of salinity and sodicity on plants

### 2.3.4 Cation exchange capacity (CEC) and plant nutrient uptake

Cations are positively charged ions such as calcium (Ca<sup>2+</sup>), magnesium (Mg<sup>2+</sup>), potassium (K<sup>+</sup>), sodium (Na<sup>+</sup>) hydrogen (H<sup>+</sup>) (H<sup>+</sup>), aluminum (Al<sup>3+</sup>), iron (Fe<sup>2+</sup>), manganese (Mn<sup>2+</sup>), zinc (Zn<sup>2+</sup>) and copper (Cu<sup>2+</sup>). The capacity of the soil to hold on to these cations called the cation exchange capacity (CEC). As a result of electrostatic forces, these cations are held by negatively charged clay and organic particles in the soil. The cations on the exchange complexes of soil particles and organic matter are easily exchangeable and as a result, they are plant available (Ketterings, Reid & Rao, 2007:1).

Cation adsorption is the process by which a negatively charged surface adsorbs positive ions. Negative clay crystal surfaces attract positively charged ions to balance the charge. Soil organic matter (SOM) has a colloidal structure with many unfilled negative charge sites. These organic molecules have structures similar to R-C-O-OH. The end sites are capable of loosely holding cations. When an ion from the water phase adsorbs to a soil surface, another cation must be displaced.

For example:



This process is known as cation exchange. The quantity of ions in a soil that is able to exchange indicates the ion exchange capacity. It is often only the cations that exchange and can therefore be referred to as the cation exchange capacity (CEC). The unit that is used to describe CEC is milliequivalents per 100 grams of soil. For example if a soil has a CEC of 2 meq/100g it is capable of adsorbing 1mg of hydrogen (or its equivalent) for every 100g of soil. Or when one inspects a single cation, the equivalent amount of Ca will be 20mg because the atomic weight of Ca is 40 and the charge is  $2^+$ , therefore  $\frac{40}{2} = 20$ . This is equal to 1meq of Ca (Winegardener, 1995:105-106).

Figure 6 illustrates cations adsorbed to negative charge sites on a soil particle and the availability thereof to exchange with other cations.

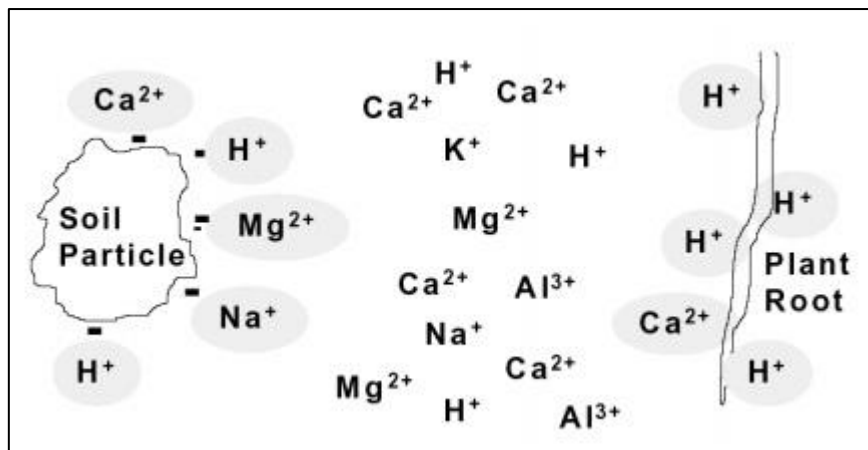


Figure 6: Adsorption of cations to negatively charged exchange complexes

The processes by which nutrient and therefore ion-uptake in soils happens, will now be further explained. For uptake to occur, an ion must be adjacent to the plant root. This process of positioning occurs either through root interception, mass flow or diffusion. Root interception happens when the plant root “bumps into” ions on the soil exchange complexes, as it grows through the soil. The nutrients that are in solution in the plant water are taken up through the roots by mass flow. These nutrients are taken up directly in solution with the plant water. Diffusion is another process by which ions that are strongly adsorbed to the soil surface and present in small quantities are taken up by the plant roots. As uptake of these ions by the plant roots increases, the concentration of the same ions in close proximity to the soil solution decreases (Mengel, 1995:4-5).

### 2.3.5 Mineralization and immobilization of plant nutrients- C: N ratio

Mineralization is the conversion of C,N,P and S from organic to inorganic forms. When conversion from inorganic form to organic form takes place, it is known as immobilization. The ratio between these elements is what dictates if mineralization or immobilization will occur. The reaction of mineralization and immobilization proceeds according to the C: N ratio. If the C: N ratio is more than 30, there is not enough N for microorganisms to incorporate C into their tissue. N is then immobilized by microorganisms to meet their needs until the C: N

ratio drops below 30. N is mineralized if the ratio drops below 20 (Fertilization Society of South Africa, 2007:32).

### 2.3.6 Soil organic matter and organic carbon

A fundamental understanding of the different components of soil carbon is necessary to avoid confusion between key components e.g. total carbon and total organic carbon. The total carbon content of a soil is the sum of the organic, inorganic and elemental carbon. Total organic carbon refers specifically to organic carbon compounds, therefore carbon from organic matter. Organic matter is difficult to measure in laboratories and therefore total organic carbon is measured instead. Organic carbon influences many soil properties and characteristics including colour, CEC, nutrient turnover and stability, which in turn influences hydrological characteristics and aeration. If a soil has high clay content the CEC can usually be contributed to the clay particles rather than to organic carbon. In a sandier soil, the total CEC may be contributed more to the fraction of organic carbon. This indicates that the CEC of the sandy soil is largely due to the organic carbon content and not to a clay fraction. Organic carbon serves as nutrition for micro-organisms which help to improve soil stability by binding soil particles together in peds or aggregates. Bacteria excretions, root exudates, fungal hyphae and plant roots can all contribute to better soil structure. If the rate of organic matter addition is greater than the rate of decomposition, the organic fraction in a soil will increase. Conversely, if the rate at which organic matter is added to soil is lower than the decomposition rate, the organic fraction will decline (Pluske, Murphy & Sheppard, 2013).

Soil organic matter (SOM) includes all the organic compounds in the soil excluding material that is still decaying. SOM can be defined as animal and plant residues in different stages of decomposition, the substances and breakdown products formed by chemical or microbiological synthesis as well as the decomposed remains of micro-organisms. Humic substances as well as resynthesized products of micro-organisms are classified under the term humus. SOM improves soil structure, water holding capacity, aeration and aggregation. It also acts as an important source of macronutrients such as N,P and S and for micronutrients such as B and Mo. Table 4 provides definitions for the various components of SOM and humic substances (Sparks, 2003:75-76).

**Table 4: Definitions of SOM and Humic substances**

<b>Term</b>	<b>Definition</b>
Organic residues	Undecayed plant and animal tissue and partial decomposition products
Soil biomass	Organic matter present as live microbial tissue
Humus	Total of the undecayed plant and animal tissues, their partial decomposition products and the soil biomass
Soil Organic Matter	Same as humus
Humic substances	High molecular weight, brown to black colored substances formed by secondary synthesis. These materials are distinctly dissimilar to the biopolymers from microorganisms and plants.
Nonhumic substances	Compounds belonging to known classes of biochemistry, e.g. amino acids, carbohydrates and fats.
Humin	The alkali insoluble fraction of soil and organic matter or humus.

Humic acid	Dark colored organic material that can be extracted from soil by various agents and is insoluble in dilute acid.
Fulvic acid	The colored material that remains after humic acid has been removed from the soil.
Hymatomelanic acid	Alcohol soluble portion of humic acid

(Sparks, 2003:76)

The SOM also greatly affects the CEC. SOM is an important sorbent of plant nutrients, heavy metal cations and organic compounds such as pesticides and herbicides. Adding SOM to soil can thus improve the nutrient uptake (Sparks, 2003:77).

Table 5 summarizes the general properties of SOM and the effects it has on a growth medium.

**Table 5: Summary of the properties and effects of SOM**

Property	Remarks	Effect on soil
Colour	Darkens the soil	Lowers albedo; soil warming
Water retention	Organic matter can hold up to 20 times its own weight in water	Helps prevent drying and shrinking. Better moisture retention by sandy soils. More plant available water
Combination with clay minerals	Cements soil particles into peds or aggregates	Stable structure. Better gas exchange between pores. Increased permeability
Chelation	Forms stable complexes with Cu, Mn, Zn and other polyvalent cations	May enhance the availability of micronutrients to higher plants
Solubility in water	Because of association with clay SOM is insoluble. Salts of divalent and trivalent cations also remain insoluble. Isolated organic matter is partially soluble in water	Organic matter loss through leaching is little
Buffer action	Organic matter exhibits a buffer capacity in slightly acidic, neutral and alkaline ranges	Maintains a uniform reaction in the soil
Cation exchange and anion adsorption	Total acidities of isolated fractions of humus range from 300 to 1400 cmol.kg <sup>-1</sup>	Increases CEC
Mineralization	Decomposition yields CO <sub>2</sub> , NH <sup>4+</sup> , NO <sup>3-</sup> , PO <sub>4</sub> <sup>3-</sup> and SO <sub>4</sub> <sup>2-</sup>	Acts as a source of nutrients for plant growth
Combines with organic chemicals	Affects biodiversity, persistence and biodegradability of pesticides	Modifies application rates of chemicals used for active control

(Sparks, 2003:78)

## 2.4 Specific stresses experienced by plants

### 2.4.1 Chlorophyll fluorescence

Chlorophyll fluorescence analysis is one of the most reliable tools available to plant physiologists. In assessing the photosynthetic performance of plants it has become very important to assess the chlorophyll fluorescence data. The principle of chlorophyll fluorescence can be explained as follow:

Three things can happen to light energy once absorbed by chlorophyll molecules inside a leaf.

- It can drive photosynthesis (photochemistry)
- Excess energy can be dissipated as heat, or
- Re-emitted as light i.e. chlorophyll fluorescence

(Maxwell & Johnson, 2000:659)

Because these processes occur in competition with each other, an increase in efficiency of one will mean a proportional decrease in the others. Therefore, measuring the yield of chlorophyll fluorescence provides information about changes in the efficiency of photochemistry and heat dissipation. Although the total amount of chlorophyll fluorescence is very small (only 1 or 2% of total light absorbed), measurement is quite easy. The spectrum of fluorescence is different to that of absorbed light, with the peak of fluorescence emission being of longer wavelength than that of absorption. Therefore, fluorescence yield can be quantified by exposing a leaf to light of defined wavelength and measuring the amount of light re-emitted at longer wavelengths. It is important to note, however, that this measurement can only ever be relative, since light is inevitably lost. Hence, all analysis must include some form of normalisation, with a wide variety of different fluorescence parameters being calculated (Maxwell & Johnson, 2000:660).

One modification to basic measuring devices that has been instrumental in revolutionizing the application of chlorophyll fluorescence is the use of a 'modulated' measuring system (Quick and Horton, 1984:361-370).

In these systems, the light source used to measure fluorescence is switched on and off at high frequency and the detector is tuned to detect only fluorescence excited by the measuring light. The relative yield of fluorescence can now be measured in the presence of background illumination, and, most significantly, in the presence of full sunlight in the field. Most modern fluorometers use such modulated measuring systems and anyone considering investing in a fluorescence system is strongly advised to select a modulated fluorometer (Maxwell & Johnson, 2000:660).

Faul & Van Deventer (2014) did thorough research on the chlorophyll fluorescence of four of the species discussed in this paper, planted on the same mine tailings. The results of their research are included and referenced in *Chapter 4 – Results*.

## Chapter 3 - Materials and methods

### 3.1 List and geology of growth mediums

Nine different types of tailings are used as growth mediums and one control of red sandy loam. The selected tailings are from mining practices and ore extracted on a large scale in South Africa, and therefore being the most pressing to find innovative and effective vegetative rehabilitation options for. The different tailings are numbered from T1 (gypsum) to T9 (fine coal tailings) with the control being TC.

The following tailings in Table 6 are used as growth mediums:

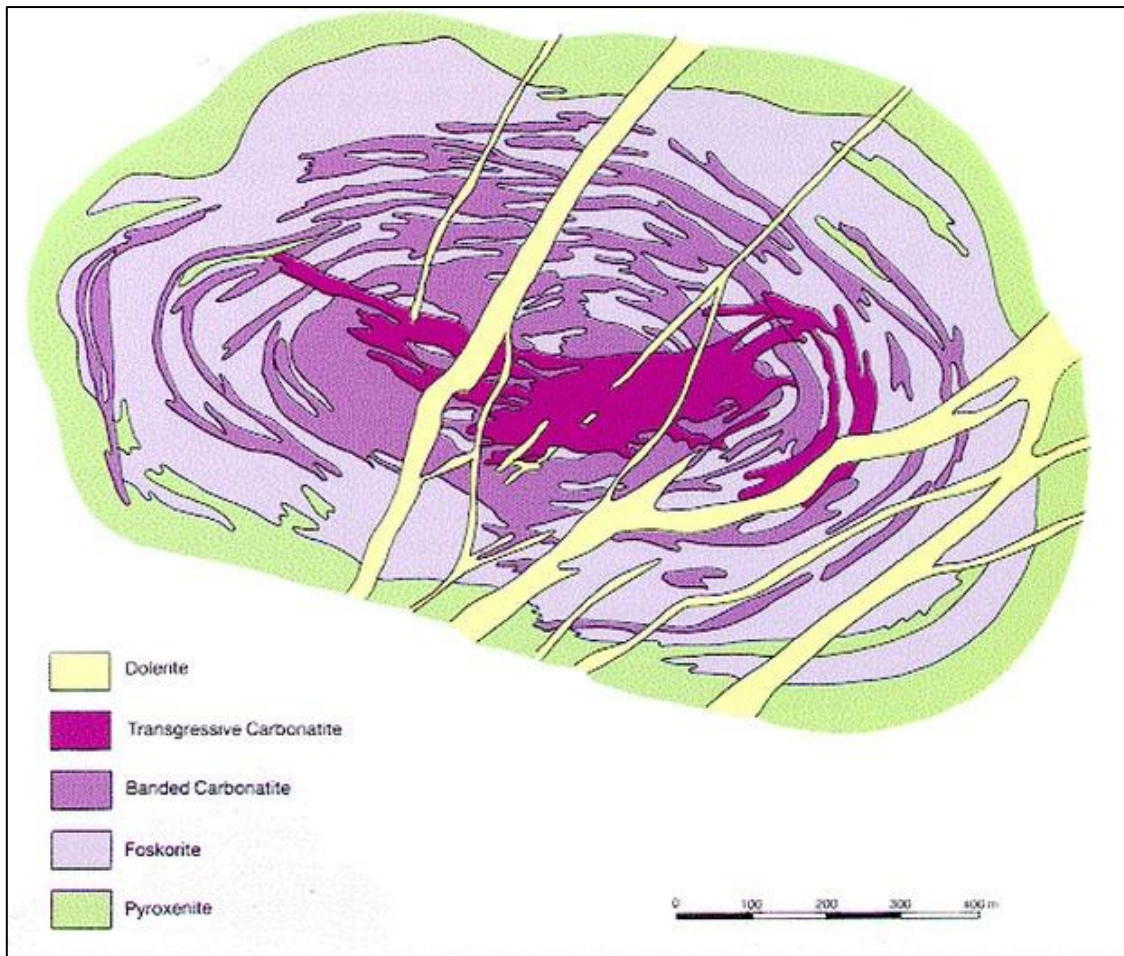
**Table 6: Types of tailings used and tailings numbering system**

Tailings	Origin	Number
Gypsum	Potchefstroom	T1
Gold with < 1% pyrite	ChemWes TDF 4	T2
Gold with > 2% pyrite	ChemWes TDF 5	T3
Platinum	Rustenburg	T4
Kimberlite	Cullinan	T5
Coal discard tailings	Witbank	T6
Fluorspar	Zeerust	T7
Andalusite	Groot Marico	T8
Coal fine tailings	Witbank	T9
Red sandy loam	Control	TC

#### 3.1.1 T1- Gypsum

The gypsum tailings (T1) are the by-product of acid treatment of phosphate rock. Phosphor is extracted in this process and used to manufacture fertilizer. The phosphor is extracted from pyroxenite, occurring in the phoscorite rocks that originate in the Phalaborwa Complex, immediately south of the town of Phalaborwa in the Limpopo province (Verwoerd & Du Toit, 2006).

The geology of the Phalaborwa Complex according to Cairncross & Dixon (1995:111) is illustrated by Figure 7.



**Figure 7: Geology of the Phalaborwa complex**

### 3.1.2 T2/T3- Gold

The gold tailings (T2 and T3) come from gold mining operations near Stilfontein in the North West province. The gold ore was mined from the Klerksdorp Goldfield. This forms part of the Witwatersrand Supergroup. The Central Rand Group, which have provided the bulk of all ore mined in the area, is almost entirely buried under younger cover, and only the West Rand Group crops out to any significant extent (McCarthy, 2006:168).

The Vaal Reef formation is the geological unit that is of major economic significance in the area. The Vaal Reef marks the base of the Krugersdorp Formation, and lies on a pronounced disconformity. The disconformity locally shows pronounced channel incision. The channels are often filled with shales and argillaceous quartzites. The channel deposits are overlain by conglomerates that contain boulders, including quartzite, up to 30 cm in diameter, and are locally well mineralized, but none is economic (McCarthy, 2006:168).

The Vaal Reef formation varies from a bitumen seam to a 1 m thick conglomerate. It is well mineralized with both gold and uranium. It is overlain by a siliceous quartzite some 3 m thick, which fines upwards to a shaly quartzite. The overlying geological units include the Krugersdorp, Booyens, Kimberley and Elsburg formations (McCarthy, 2006:168).

### 3.1.3 T4- Platinum

The T4 platinum tailings are from the extensive mining operations done by Anglo American Platinum. The mining operations consist of mines across South Africa. These mines extract ore from the Merensky and Upper Group No. 2 (UG2) reefs, located in the critical zone of the Rustenburg Layered Suite, which form part of the Bushveld Igneous Complex (Louw, 2013).

The stratigraphy of the Rustenburg Layered Suite is illustrated by Figure 8 (Manyeruke, 2003:107).

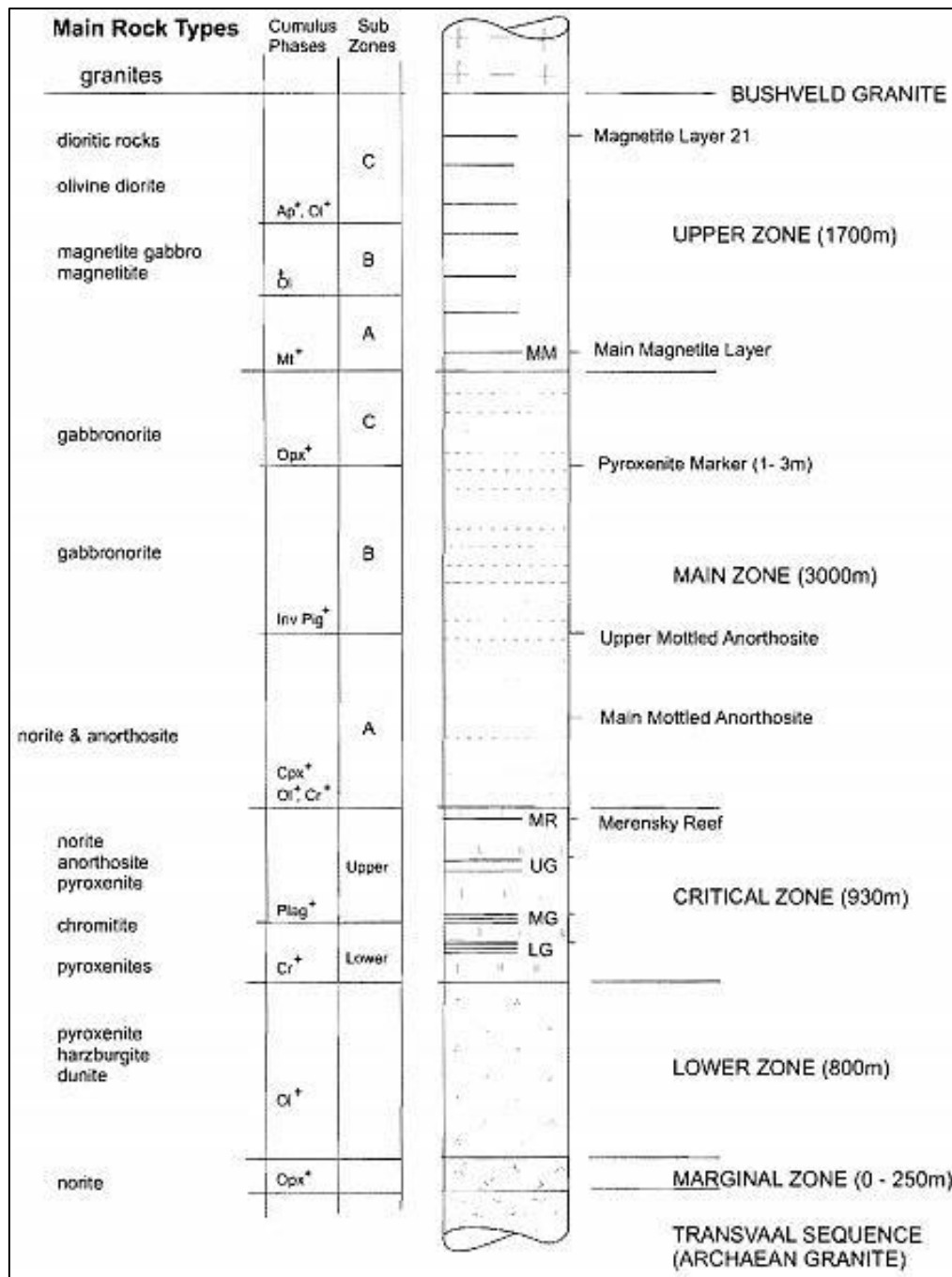


Figure 8: Stratigraphy of the Rustenburg layered suite

### **3.1.4 T5- Kimberlite**

The T5 kimberlite tailings are from the Cullinan kimberlite pipe, which occurs within the stable, three billion year old Kaapvaal Craton and intrudes rocks of the Transvaal Supergroup (Pretoria Groups), Bushveld Igneous Complex (Rooiberg Group) and the younger Waterberg Group. It is a Group 1 kimberlite and it is estimated by geological inference that the top 300 m of the original pipe has been eroded away since the pipe was intruded 1,200 million years ago (Chadwick, 2012:1).

The pipe has numerous facies. However there are three dominant facies, namely the brown tuffisitic kimberlite breccia (TKB), the grey TKB and the hypabyssal facies, which is contained within the grey TKB. The pipe has intruded through a variety of rocks, the most important of which is norite, the rock type in which most of the current mine haulage system is based. The norite has been correlated with the main zone of the Bushveld Complex. Quartzites, shales, sandstones and dolomitic shales of the Transvaal Supergroup occur both above and beneath the norite. A unique feature of this kimberlite is the occurrence of an approximately 70-m thick diabase sill (varies from gabbro to norite) that cuts across the occurrence at approximately the 500 m elevation. Mining has progressed well below this horizon with no deleterious effect (Chadwick, 2012:1).

### **3.1.5 T6/T9- Coal**

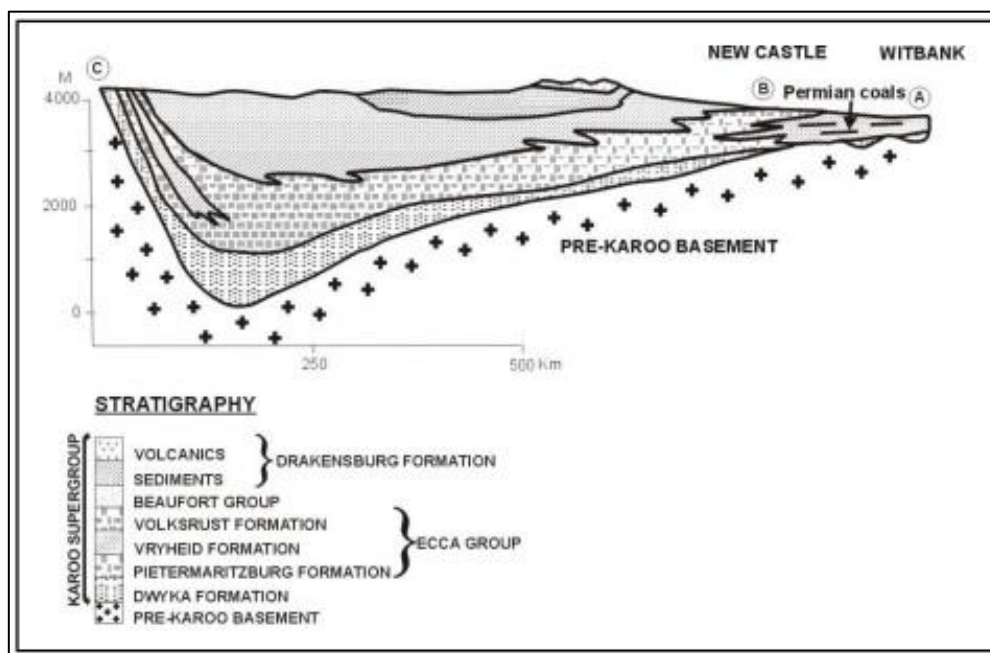
The T6 and T9 coal tailings originate from the Witbank coal seam, which is situated on the northern sector of the Karoo Supergroup. The Karoo basin is described as an asymmetric depository with a stable cratonic platform, the Kaapvaal Craton more specifically, in the northwest and a foredeep to the south with the Cape Fold Belt on its southern margin. The stable Kaapvaal Craton in the northern sector of the basin is reflected by the sedimentary depositional manner of the Eccca Group of rocks, as well as the Permian peat (coal) accumulated on parts of this stable shelf area. These sedimentary rocks have never been subjected to deep burial, intense tectonic stresses or high geothermal gradients (Du Plessis, 2008:2-3).

Stratigraphically the Eccca Group consists of the basal Pietermaritzburg Formation overlying the Vryheid and Volksrust Formations conformably. The proximal coarse fluvio-deltaic sandstones of the Vryheid Formation were mainly derived from a northern source and thin towards and wedge southwards into the siltstones and mudstones of the Pietermaritzburg and Volksrust Formations. These fluvo-deltaic sandstones were deposited in the intracratonic Eccca Sea. Coal seams that developed in the Witbank Coalfield are contained within the Vryheid Formation, ranging in thickness between 80m and 200m. Five mineable bituminous coal seams are present from No.1 at the base to No.5 at the top. A simplified stratigraphic column explaining the basic geology is given in Table 7 (Du Plessis, 2008:3).

**Table 7: Stratigraphic column of the Karoo Supergroup in the northern portion of the Karoo basin**

PERIOD (AGE)	GROUP	FORMATION	ROCK TYPES
<i>Jurassic (150 my)</i>		Drakensberg	Basaltic lava
Triassic (195 my)		Clarens	Fine-grained sandstone
		Elliot	Red sandstone, mudstone
		Molteno	Sandstone, sub-ordinate coal
Permian (225 my)	Beaufort	Tarkastad	Sandstone, shale
		Estcourt	Sandstone, shale, sub-ordinate coal
	Ecca	Volkstrust	Shale, sandstone, sub-ordinate coal
		Vryheid	Sandstone, shale, coal
		Pietermaritzburg	Shale
<i>Upper Carboniferous (285 my)</i>		Dwyka	Tillite, varved shale

A cross section of the Karoo Supergroup, indicating the Witbank Permian coals, is illustrated by Figure 9 (Du Plessis, 2008:2).



**Figure 9: Cross section of the Karoo Supergroup, indicating the Witbank coals**

### 3.1.6 T7- Fluorspar

The T7 Fluorspar tailings come from the Witkop Fluorspar Mine which is situated some 18 km south of the town of Zeerust in the North West province. The fluorspar deposits occur as large stratabound bodies in a well-defined stratigraphic unit in the upper part of the Malmani dolomite sequence. They also appear to be closely related to a major south-south-westerly-trending fault or fracture zone. Mineralogical investigations have shown that fluorspar, late stage quartz, and base metal sulphides are clearly secondary replacements within the host dolomitic limestone, and no evidence of a syngenetic origin for the fluorspar could be found (Ryan, 1986:843).

### 3.1.7 T8- Andalusite

The T8 andalusite tailings originate from deposits that are situated in the thermal aureole of the Palaeoproterozoic Bushveld Igneous Complex (BIC) which intrudes the Transvaal Supergroup (2600-2100 Ma). Andalusite is developed in weakly deformed meta-pelitic rocks of the Pretoria Group representing the uppermost succession of the Supergroup. The thermal effect of the magmas can be traced up to 55 km away from the exposed intrusive contacts and caused the zonal development of metamorphic mineral assemblages in the pelitic rocks, including an outer andalusite zone. This zone fluctuates parallel with the contact of the mafic intrusions of the BIC and cuts across the sedimentary layering as in the Lydenburg district. Figure 10 illustrates the geology of the area (Ihlen, 2000:120-121).

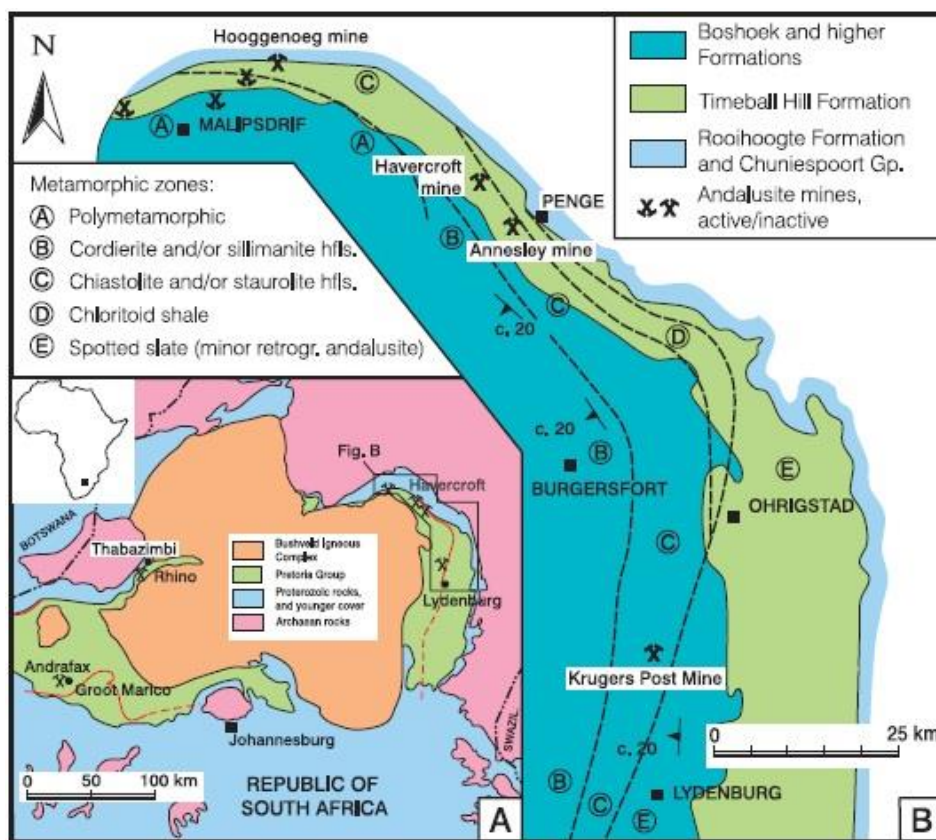


Figure 10: Geology surrounding the Andalusite mines of the BIC

Figures 11 to 13 are pictures of some of the different tailings in potting bags.



Figure 11: Coal discard tailings



Figure 12: T5- Kimberlite; T7- Fluorspar; T8- Andalusite; TC- Control



Figure 13: T9- Coal fine tailings

### 3.2 List and description of selected species

The scientific and common names of the selected species are listed in Table 8:

**Table 8: List of established species**

	Scientific name	Common name
1.	<i>Acacia caffra</i>	Hook thorn
2.	<i>Acacia karroo</i>	Sweet thorn
3.	<i>Searsia lancea</i>	Karee
4.	<i>Searsia pyroides</i>	Currant
5.	<i>Buddleja saligna</i>	False olive
6.	<i>Olea europaea subsp. africana;</i>	Wild olive
7.	<i>Combretum erythrophylum</i>	River bushwillow
8.	<i>Celtis africana;</i> White stinkwood	White stinkwood
9.	<i>Eucalyptus macarthurii</i>	Eucalyptus
10.	<i>Vetiveria zizanioides</i>	Vetiver
11.	<i>Bambusa glaucescens</i>	Hedge bamboo
12.	<i>Asparagus laricinus</i>	Cluster leaf asparagus
13.	<i>Schoenoplectus acutus</i>	Hardstem Bulrush
14.	<i>Cynodon dactylon</i> (variety)	Free state couch grass
15.	<i>Hyparrhenia hirta</i>	Thatch grass
16.	<i>Chloris gayana</i>	Rhodes grass
17.	<i>Cynodon dactylon</i>	Couch grass
18.	<i>Eragrostis curvula</i>	Weeping lovegrass
19.	<i>Themeda triandra</i>	Red grass
20.	<i>Cenchrus ciliaris</i>	African foxtail grass
21.	<i>Cymbopogon excavatus</i>	Broad leaf turpentine grass
22.	<i>Pavetta edentula</i>	Gland-leaved bride's bush
23.	<i>Atriplex nummularia</i>	Old man's Saltbush
24.	<i>Portulacaria afra</i>	Elephant bush
25.	<i>Cymbopogon excavatus</i>	Broad leaf turpentine grass
26.	<i>Grewia flava</i>	Velvet raisin
27.	<i>Diospyros lycioides</i>	Transvaal bluebush
28.	<i>Sericea lespedeza</i>	Poor man's lucerne
29.	<i>Psathyrostachys junceus</i>	Russian wildrye grass

### 3.2.1 *Acacia caffra*; Hook thorn

- Small to medium-sized deciduous tree, crown rounded with drooping foliage.
- Hooked thorns that are paired at nodes.
- Fresh green and feathery leaves that are bipinnately compound.
- Petiolar gland usually present but not distinctly stalked.
- Flowers in elongated spikes.
- Pods are flat.
- Pod colour varies from pale brown to reddish brown.

(Van Wyk & Van Wyk, 2011:29)

### 3.2.2 *Acacia karroo*; Sweet thorn

- Shrub to medium-sized deciduous tree; crown rounded, dark green.
- Rough, longitudinally fissured blackish to grey-black bark.
- Spines paired, straight, white, and more prominent on young plants.
- Bipinnately compound leaves.
- Flowers are bright yellow and in globose heads.
- Sickle shaped flat pods that are slightly constricted between seeds, dehiscent and with brittle valves

(Van Wyk & Van Wyk, 2011:33)

### 3.2.3 *Searsia lancea*; Karee tree

- Evergreen.
- Small to medium-sized.
- Rounded or dome shaped spreading crown with somewhat drooping branches.
- Short or multistemmed trunk.
- Dark green foliage.
- Rough dark brown to blackish bark.
- Latex present but watery with weak and inconsistent flow.
- Hairless, semi leathery leaves that are olive green above and pale yellowish-green below, tapering narrowly towards the tip, covered in a shiny exudate.
- Petiole up to 30 mm long.
- Terminal leaflet linear to lanceolate, 25-120 x 5-12 mm.
- Small greenish-yellow flowers in panicles, male and female ones on different plants.
- Fruit is a spheroidal, compressed drupe; fruits are shiny and hairless, dull yellow brown.

(Van Wyk & Van Wyk, 2011:281)

### 3.2.4 *Searsia pyroides*; Currant

- Multistemmed shrub or small to medium-sized tree usually with leafy branches from ground level.
- Older branches become spiny.
- Young twigs present velvety hairs.
- Latex present but watery with inconsistent flow.

- Leaves alternate and trifoliate with sessile leaflets.
- Leaves are dull olive green above and paler below.
- Semi leathery leaves.
- Secondary leaf veins are raised below.
- Petiole up to 40mm long.
- Terminal leaflet lanceolate to obovate, round but tapering to a sharp point, 30-80 x 10-23 mm.
- Flowers small, greenish-yellow and in panicles.
- Male and female flowers on different plants.

(Van Wyk & Van Wyk, 2011:284)

### **3.2.5 *Buddleja saligna*; False olive**

- Evergreen large shrub or small tree.
- Leaves petiolate; linear to lanceolate; grey-yellow on underside due to a dense covering of stellate scales; margin entire inrolled; veins anastomosing to form a line parallel to margin.
- Flowers (Aug-Jan) borne in three flowered velvety cymes; small bowl shaped with anthers exerted; cream with orange throat; faintly scented.

(Verdoorn, 1963:160)

### **3.2.6 *Olea europaea* subsp. *africana*; Wild olive**

- Small to medium sized; short trunk that is often gnarled and crooked.
- Dense round or dome shaped crown.
- Evergreen; foliage grayish green.
- Greyish twigs often with white lenticels.
- Leaves opposite; narrowly oblong-elliptic; 7-17 mm wide; shiny dark green above and grayish below; sharply pointed tip; margin entire, rolled under; side veins distinct.
- Very small white or cream flowers in loose, axillary or occasionally terminal heads
- Fruits are purplish black, ovoid drupes; about 10 x 8 mm.

(Van Wyk & Van Wyk, 2011:215)

### **3.2.7 *Combretum erythrophyllum*; River bushwillow**

- Short trunked, medium-sized to large deciduous tree.
- Trunk usually single and branching low down.
- Roundish, sparse crown with medium green foliage often whitish in spring and reddish in autumn.
- Smooth bark; cream to pale orange-brown often with grey mottles.
- Leaves are opposite, alternate or 3-whorled, elliptic to oblong-elliptic; distinctly hairy; 50 x 20 mm.
- Flowers yellow-green in short, axillary spikes.
- Greenish brown 4-winged fruits; about 15 x 12 mm.

(Van Wyk & Van Wyk, 2011:89)

### 3.2.8 *Celtis africana*; White stinkwood

- Medium-sized to large deciduous tree.
- Single, upright trunk.
- Rounded crown; dark green foliage.
- Bark pale grey and quite smooth.
- Leaves alternate, simple, with three prominent veins from the base; lamina ovate; colour is dull green often with a broad yellow zone around the margin caused by an as yet unidentified disease; base asymmetric; margin toothed over the upper half.
- Axillary flowers; male and females on the same plant.
- Fruits are ovoid yellow brownish drupes; about 6 mm in diameter.

(Van Wyk & Van Wyk, 2011:83)

### 3.2.9 *Eucalyptus macarthurii*; Eucalyptus

- Tree up to 40 m high; grey-brown bark persistent on trunk and large branches; shortly fibrous; thick; smooth above; shedding in short ribbons.
- Juvenile leaves opposite; ovate to broad-lanceolate; cordate; dull green.
- Adult leaves disjunct; narrow-lanceolate; 8-16 cm long; 0.8-1.5 cm wide; green; dull; concolorous. Umbellasters 7-flowered; peduncle narrowly flattened or angular; 2-9 mm long; pedicels terete; 1-2 mm long.
- Buds ovoid or fusiform; 3-5 mm long; 2-3 mm diam; scar present; calyptra hemispherical or conical, shorter than or as long as and as wide as hypanthium.
- Fruit hemispherical; conical or campanulate; 3-5 mm long; 3-6 mm diam; disc raised; valves exerted.

(Hill & Harden, 2002:132)

### 3.2.10 *Vetiveria zizanioides*; Vetiver

- Tall and hardy bunch grass, reaching about 2 m with maturity.
- Grows on soils ranging between sandy duplex soils to clay-rich soils.
- Used for soil conservation, acting as a living contour, that is as a barrier being planted on contours to trap soil while water flows through.
- Strong with very deep root system that can reach up to 5 m. These roots can penetrate compacted soil layers with minimal lateral growth. This makes vetiver grass tolerant to droughts.
- Can tolerate extreme soil conditions e.g. pH 3-10, high aluminium, sodicity and moderate salinity.
- Can tolerate harsh climactic conditions ranging from droughts to waterlogging.
- Tolerant to high concentrations of cadmium, lead, arsenic and mercury.
- Low palatability.
- Planted vegetatively as splits, at 1m spacing in rows; spreads slowly by short rhizomes to form a large clump.

(Moore & Stanton, 2006)

### 3.2.11 *Bambusa glaucescens*; Hedge bamboo

- Clump-forming bamboo that forms dense clumps but that do not run extensively.
- Stems are usually 3000 – 5000 mm x 10 – 20 mm.
- Culm sheaths with black hairs that are soon shed.
- Several branches at each node.
- Leaf blade is linear-lanceolate.
- Leaf blade: 60 – 150 mm long; 6 – 15 mm wide; glaucous and hairy underneath.

(New Zealand Plant Conservation Network, 2013)

### 3.2.12 *Asparagus lariginus*; Cluster leaf asparagus

- Spiny shrub that grows 1 – 3 m in height.
- Distributed through Southern Africa.
- Apart from growing on and around gold tailings dams in the Witwatersrand basin, *A. lariginus* has also shown high seed production and viability in polluted soils. (Wanenge, 2012:41)
- Scrambling shrub or climber. Stems whitish with short hard spines; cladodes (leaf-like modified branchlets) in clusters of up to 60, 2.5 - 3.5 cm long; flowers white, on the outside of cladode clusters.
- Fruits are red

(Pickering & Roe, 2009:30)

### 3.2.13 *Schoenoplectus acutus*; Hardstem Bulrush

- Perennial, rhizomatous species reaching up to 3 m in height.
- Forms very dense stands.
- Upright, dark-green stems.
- Few, short leaves with a well-developed sheath, found near the base.
- Inflorescence is a terminal panicle of three to ten spikes, made up out of more spikelets (up to 50).
- Each spike may be on a short pedicel or sessile.
- Fruit is a dark-brown lenticular achene up to 2.5 mm long.
- Forms large stands, often monoculture; younger plants on the outside, older plants centre.
- Generally in areas of standing water; not tolerate of deep water for very long periods.
- Grows on substrates ranging from peat to coarse soils.
- Adapted to alkaline, saline and brackish soils.
- Re-sprouts after fire.
- Reproduces from seed and rhizomes.
- Excellent choice for soil stabilization due to dense root mass.
- Above ground biomass protects soil from water erosion.
- Rhizomatous root mass acts as ecosystem for many types of beneficial bacteria.

(Tilley, 2012:1-2)

### **3.2.14 *Cynodon dactylon* (variety); Free State couch grass**

- This grass is a variety of 3.2.17, sampled specifically from areas in the Free State, South Africa

(see 3.2.17 *Cynodon dactylon* for features).

### **3.2.15 *Hyparrhenia hirta*; Thatch grass**

- Dense, erect, perennial tufted grass.
- Spikelets covered with white to grey hairs.
- Four to seven hairy, brown awns on every raceme.
- Often forms dense stands on roadsides and old cultivated lands.
- Culms height varies with rainfall.
- Flowers September – March.
- Culms: 300 – 1500 mm
- Inflorescence: 200 – 400 mm.
- Racemes: 20 – 40 mm.
- Spikelets: 4 – 6.5 mm.
- Awns: 10 – 35 mm.
- Leaf blade: 20 – 150 mm long; 1 – 4 mm wide.
- This grass is a popular source for thatching.
- Palatable early in the growing season.
- Drought resistant; protects soil and stabilizes hard, gravelly soil and eroded areas.

(Van Oudtshoorn & Van Wyk, 1999:56)

### **3.2.16 *Chloris gayana*; Rhodes grass**

- Very leafy grass; spreads by means of stolons.
- Inflorescence is digitate, with loose fingers that curl after spikelets fall off.
- Compressed leaf sheaths.
- Leaf blade folded open and smooth.
- Spikelets are brown with two awns.
- Flowers November – May.
- Culms: 500 – 1200 mm.
- Spikes: 50 – 130 mm.
- Spikelets: 3 – 5 mm.
- Awns: 1 – 10 mm.
- Leaf blade: 250 – 500 mm long; 3 – 9mm wide.
- Very good grazing grass.
- Easy to establish.
- Very suitable for stabilization of disturbed soil.

(Van Oudtshoorn & Van Wyk, 1999:230)

### **3.2.17 *Cynodon dactylon*; Couch grass**

- Short, mat-forming grass which spreads by means of stolons and rhizomes.
- Inflorescence exclusively digitate.
- Flat spikelets without awns.
- Grows in disturbed places.
- Leaves point upwards.
- Flowers September – May.
- Culms: 50 – 400 mm
- Racemes: 20 – 60 mm.
- Spikelets: 2 – 2.5 mm.
- Leaf blade: 10 – 120 mm long; 2 – 4 mm wide.
- Good pasture, can endure heavy grazing.
- Stolons and rhizomes make it an excellent soil stabilizer, however difficult to control mechanically.

(Van Oudtshoorn & Van Wyk, 1999:229)

### **3.2.18 *Eragrostis curvula*; Weeping lovegrass**

- Robust, densely perennial tufted grass.
- Produces many long, loose, hanging leaves.
- Inflorescence mostly an open panicle, contracted panicle in Northern, Western and Eastern Cape.
- Spikelets dark grey to dark olive green.
- Leaves often concentrated to base of plant.
- Flowers August – June.
- Culms: 300 – 1200 mm.
- Inflorescence: 100 – 300 mm.
- Spikelets: 4 – 10 mm.
- Leaf blade: up to 400 mm long; up to 4 mm wide.
- Popular pasture (palatable).
- Easy to establish and responds well to fertilization.
- One of the best grasses to stabilize disturbed soil.

(Van Oudtshoorn & Van Wyk, 1999:177)

### **3.2.19 *Themeda triandra*; Red grass**

- Varying perennial tufted grass.
- Inflorescence comprises groups of spikelets (often pendent) partially enclosed by a spathe.
- Each spikelet pair has a long, dark, twisted awn.
- Compressed leaf sheaths.
- Leaf blade has a prominent midrib.
- Dark colored nodes.
- Ligule usually has a notch at the point.
- Late in the season the plant has a red colour.
- Flowers October – July.

- Culms: 300 – 1500 mm.
- Inflorescence: 100 – 250 mm.
- Spikelets: 5 – 7 mm.
- Awns: 25 – 60 mm.
- Leaf blade: 150 – 300 mm long; 1 – 8 mm wide.
- Palatable.
- The main value of Red grass lies in the fact that it is usually dominant in the veld and can form dense stands.
- Fire resistant.
- Red grass is an indicator of a healthy system.

(Van Oudtshoorn & Van Wyk, 1999:50)

### **3.2.20 *Cenchrus ciliaris*; African foxtail grass**

- Perennial tufted grass with a shrub-like growth form.
- Inflorescences are a dense purple to straw colored spike.
- When mature, the entire spikelet falls off.
- Spikelets are surrounded by wavy bristles arising from a short stalk.
- Culms have multiple branches.
- Flowers August – April.
- Culms: 600 – 1000 mm.
- Inflorescence: 40 – 120 mm.
- Spikelets: 2 – 5 mm.
- Leaf blade: 100 – 250 mm long; 4 – 10 mm wide.
- Good grazing grass with high leaf production and palatability.
- Hardy, with a deep root system (up to 2 m).
- Hard to establish in clay soil, but grows once established.

(Van Oudtshoorn & Van Wyk, 1999:88)

### **3.2.21 *Cymbopogon excavatus*; Broad leaf turpentine grass**

- Leaves and inflorescence have a strong turpentine smell when crushed.
- Erect grass; leaves are situated high up on the culms; often used for thatching.
- Base of leaf blade is much wider than the thickness of the culm.
- Leaves are bright green with a prominent midrib.
- Some leaf parts often covered in a white waxy layer.
- Culms mostly unbranched.
- Flowers November – May.
- Culms: 500 – 1500 mm.
- Inflorescence: 80 – 250 mm.
- Racemes: 6 – 10 mm.
- Spikelets: 3.5 – 5 mm.
- Leaf blade: 50 – 300 mm long; up to 14 mm wide.
- Not very palatable; grazers will only utilize this species if no other grass is available.
- Contains an essential oil with almost 18 ingredients.

(Van Oudtshoorn & Van Wyk, 1999:52)

### **3.2.22 *Pavetta edentula*; Gland-leaved bride's bush**

- Shrub or small deciduous tree.
- Trunk short with branches starting low down, or multistemmed.
- Sparse crown with thick, rigid, upright branches.
- Leaves opposite, clustered towards the ends of branches with interpetiolar stipules.
- Leaves are simple; lanceolate; leathery and fleshy; green; hairless; bacterial nodules circular to elliptic and scattered over the blade.
- Leaves 200 x 500 mm; petiole up to 25 mm long.
- White flowers in compact axillary clusters.
- Fleshy, globose fruit; up to 8 mm in diameter; black.

(Van Wyk & Van Wyk, 2011:226)

### **3.2.23 *Atriplex nummularia*; Saltbush**

- *A. nummularia* is widely planted on saline soils as a vegetative cover. Such plantations also use the saline groundwater and therefore affect the salinity thereof.
- Erect shrub growing up to 2 m high and 2.4 m wide.
- Branches are white.
- Leaves are oval to almost round; grey; up to 2 cm long.
- Terminal flowers small and green.
- Triangular, laterally compressed fruits; 10 – 20 mm.
- Good drought and salt tolerance and grows well in deep soils with only 150 – 250 mm of rain annually.
- Resists temperatures as low as -10°C; frost resistant.
- *A. nummularia* can efficiently be propagated from stem cuttings especially during spring. In the summer it may be susceptible to diseases.

(Aganga *et al.*, 2003:72-73)

### **3.2.24 *Portulacaria afra*; Elephant bush**

- Multistemmed succulent shrub or small tree with untidy crown.
- Smooth grey shiny bark.
- Leaves opposite and simple; almost circular or obovate; up to 25 x 17 mm; fresh green or pale grey fleshy leaves.
- Flowers in many-flowered panicles, small, pale pink to purple.
- 3-winged fruit; small capsule; about 5 mm long.

(Van Wyk & Van Wyk, 2011:245)

### **3.2.25 *Grewia flava*; Velvet raisin**

- Multistemmed shrub or small deciduous tree; leafy branches from ground level with rounded crown and grey-green foliage.
- Older stems are roundish.
- Leaves alternate; simple; three-veined from base; elliptic to oblanceolate; 14 – 70 x 7 – 25 mm.
- Densely hairy leaves; grey-green above and paler green below with prominently raised veins.

- Leaf tips are rounded but with a broadly tapering base; symmetric; finely toothed.
- Yellow flowers occur in axillary clusters.
- Reddish brown fruits are globose or faintly 2-lobed drupes; about 8 mm in diameter.

(Van Wyk & Van Wyk, 2011:165)

### **3.2.26 *Diospyros lycioides*; Transvaal bluebush**

- Small to medium-sized tree, or shrub; ascending branches; usually multistemmed.
- Dark grey to almost black bark; smooth.
- Leaves alternate, simple, entire margined, oblanceolate; 15-80 x 5-30mm; mature blade hairless with venation.
- Flowers axillary, solitary, drooping, creamy yellow; male and female ones on different plants.
- Fruits are globose berries up to 20mm in diameter; hairy; ripening from yellow to orange to red; calyx persistent and enlarged.

(Van Wyk & Van Wyk, 2011:118)

### **3.2.27 *Sericea lespedeza*; Poor man's Lucerne**

- Widely adapted, non-bloating, warm-season perennial legume.
- Uses include grazing, hay or as a conservation plant.
- Grows best on deep, well drained soils, but adaptable to a wide range of soil types.
- Responds well to fertilization, but can be grown in substrates too acidic for other legumes.
- Hard to adapt to extremely dry, shallow or alkaline soils.
- *Sericea* is a legume and therefore doesn't require N fertilization and it increases the N content of the substrate.
- Because of the deep root system, *S. lespedeza* is drought resistant and a good soil stabilizer.
- Good seed producer which is resistant to insects and diseases.
- The shedding of lower leaves creates a mulch that improves soil texture, increases soil organic matter and prevents erosion.

(Ball & Mosjidis, 2007)

### **3.2.28 *Psathyrostachys junceus*; Russian wildrye grass**

- Cool season, perennial, densely tufted bunchgrass; 60 – 180 cm tall.
- Flat leaves; 2 – 3 mm wide; 15 – 25 cm long; both surfaces deeply grooved.
- Leaves lax and mostly basal.
- Leaf sheaths are open; auricles rudimentary and up to 1 mm long.
- Ligule is membranous; 1 – 1.5 mm long and truncate.
- The spike is 3 – 11 cm long; disarticulating between the spikelets and is compact, cylindrical and the rachis flattened.
- Spikelets: 8 – 10 mm long; three per node and 2-flowered.
- Glumes: 4 – 6.5 mm long, subequal and the lemmas 6.7 – 8.5 mm long, tapering to an awn of 0.5 – 2 mm.
- Roots establish to depths of 180 – 240 cm.

- $\pm$  75% of the roots are in the top 15 – 60 cm and horizontal spread reaches 120 – 150 cm. Within this space the roots draw up almost all soil moisture making it an excellent competitor with weeds.
- Tolerant to drought, low temperatures and saline soils.
- Tolerant to grazing and regrows quickly.
- Well adapted to silt loam – heavy clay soil types but most productive on fertile loam soils.

(Ogle *et al*, 2012)

### 3.3 Plant growth measurements and data processing

Four to nine repetitions of each species were planted into 20L or 50L potting bags filled with each one of the tailing types. The result is a sample number for example T5-S26-2, this example being tailings material number 5 (Kimberlite), species number 26 (*Grewia flava*) and the number 2 indicating this is the second repetition. Figure 14 is a photograph of the established plants in the nursery.



**Figure 14: Established plants**

Mist jets were used as irrigation system. Plant growth was initially measured four times per year, then twice annually for a total of six measurements.

### 3.3.1 Methods used to measure plant growth

Four main parameters were measured to quantify plant growth: height of plant, diameter of base, diameter of canopy and stress factors exhibited by plants. All of the above mentioned factors, except the latter, were also used by Lange *et al.* (2012). in a pot trial studying the effects of different soil ameliorants on karee trees (*Searsia lancea*) on mine tailings.

All measurements are conducted on the plants in the pots with mine tailings. The height and canopy diameter is measured using a tape measure in centimetres (cm). Height is measured from where the stem/trunk protrudes from the tailings to the highest living branch/grass of the plant. See Figure 15.

Canopy diameter is measured in two directions perpendicular on one another also using a tape measure. This is done by placing the tape measure on top of the canopy of the plant and taking the distance from the farthest living branch on the one side to the farthest living branch on the other side. This is repeated perpendicular on the first measurement.

It is important to note that for the grass species, only height measurement was done, as canopy and basal diameter is difficult to define in the case of grasses.



**Figure 15: Height measurement using tape measure**

Basal diameter is measured by using a digital caliper as shown in Figure 16. The two ends of the calliper are positioned tight around the trunk/stem and the diameter is given in cm on the digital screen.



**Figure 16: Measurement of basal diameter using an electronic caliper**

### **3.3.2 Statistical processing of plant growth data**

The purpose and target of the data is not only to get a summary of the data, but to create a data system (program) that can be used for other research on different tailings with a variety of species.

Using Excel formulas and equations, the program allows the user to choose the role the height, basal and canopy diameter plays in the final index given.

The process are explained systematically with figures to illustrate the steps in development of the model, from the initial data to the final index. The full results are given in Chapter 4.

## STEP 1

- The initial and final growth measurements are inserted in the sheet illustrated by Figure 17.

Reference	INITIAL					FINAL				
	Height (cm)	Basal diameter (cm)			Canopy diameter (cm)	Height (cm)	Basal diameter (cm)			Canopy diameter (cm)
T1-S01-1										
T1-S01-2										
T1-S01-3										
T1-S01-4										
T1-S01-5										
T1-S02-1										
T1-S02-2										
T1-S02-3										
T1-S02-4										
T1-S02-5										
T1-S03-1										
T1-S03-2										
T1-S03-4										
T1-S03-5										
T1-S04-1										
T1-S04-2										

Figure 17: Initial and Final data input sheet

- This automatically calculates the growth averages of each of the species in the specific tailings as shown in Figure 18.

Reference	INITIAL					FINAL						
	Height (cm)	Basal diameter (cm)			Canopy diameter (cm)	Height (cm)	Basal diameter (cm)			Canopy diameter (cm)		
T1-S01-1	66.00	5.90			31.00	27.00	180.00	42.71		95.00	102.00	
T1-S01-2	90.00	13.46			68.00	50.00	87.00	18.35		46.00	70.00	
T1-S01-3	75.00	6.77	6.53	8.65	9.08	33.00	40.00	147.00	27.81		92.00	91.00
T1-S01-4												
T1-S01-5	101.00	11.37				62.00	51.00	180.00	17.04		95.00	114.00
	<b>83.00</b>		<b>8.82</b>			<b>45.25</b>	<b>148.50</b>		<b>26.48</b>		<b>88.13</b>	
T1-S02-1	24.00	16.05				43.00	52.00	80.00	26.83		167.00	106.00
T1-S02-2	25.00	6.67	3.72			27.00	55.00	120.00	42.00		151.00	99.00
T1-S02-3	70.00	9.98	6.26			66.00	70.00	168.00	31.85		201.00	171.00
T1-S02-4	29.00	6.49	8.56			30.00	12.00					
T1-S02-5	60.00	11.65				88.00	37.00	112.00	20.95		103.00	89.00
	<b>41.60</b>		<b>8.67</b>			<b>48.00</b>	<b>120.00</b>		<b>30.41</b>		<b>135.88</b>	
T1-S03-1	15.60	15.18				85.00	74.00	175.00	21.50		81.00	89.00
T1-S03-2	118.00	16.54				54.00	64.00					
T1-S03-4	158.00	15.01				60.00	56.00					
T1-S03-5	135.00	17.81				57.00	65.00					
	<b>106.65</b>		<b>16.14</b>			<b>64.38</b>	<b>175.00</b>		<b>21.50</b>		<b>85.00</b>	
T1-S04-1	134.00	16.09				68.50	75.00	170.00	29.83		80.00	57.00
T1-S04-2	122.00	13.73	4.98			43.50	48.50	135.00	44.30		64.00	60.00

Figure 18: Inserted data with calculated averages

## STEP 2

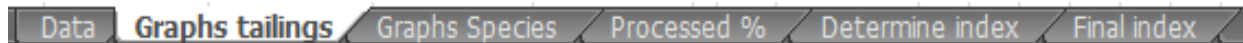
- This automatically calculates the following (Figure 19):
  - i. Increase in the growth (in cm) from the averages calculated in the previous step.
  - ii. Percentage increase in height, basal and canopy diameter.
  - iii. Number of deaths per tailings-species combination.

Reference	INITIAL						FINAL						SUMMARY						Number of deaths per combination			
	Height (cm)	Basal diameter (cm)				Canopy diameter (cm)		Height (cm)	Basal diameter (cm)				Canopy diameter (cm)		Height increase (cm)	% Growth-Height	Basal diameter increase (cm)	% Growth-Basal diameter		Canopy diameter increase (cm)	% Growth-Canopy diameter	
T1-S01-1	66.00	5.90				31.00	27.00	180.00	42.71				95.00	102.00								0
T1-S01-2	90.00	13.46				68.00	50.00	87.00	18.35				46.00	70.00								
T1-S01-3	75.00	6.77	6.53	8.65	9.08	33.00	40.00	147.00	27.81				92.00	91.00								
T1-S01-4																						
T1-S01-5	101.00	11.37				62.00	51.00	180.00	17.04				95.00	114.00								
	<b>83.00</b>	<b>8.82</b>				<b>45.25</b>		<b>148.50</b>	<b>26.48</b>				<b>88.13</b>		<b>65.50</b>	<b>79%</b>	<b>17.65</b>	<b>200%</b>	<b>42.88</b>	<b>95%</b>		
T1-S02-1	24.00	16.05				43.00	52.00	80.00	26.83				167.00	106.00								1/5
T1-S02-2	25.00	6.67	3.72			27.00	55.00	120.00	42.00				151.00	99.00								
T1-S02-3	70.00	9.98	6.26			66.00	70.00	168.00	31.85				201.00	171.00								
T1-S02-4	29.00	6.49	8.56			30.00	12.00															
T1-S02-5	60.00	11.65				88.00	37.00	112.00	20.95				103.00	89.00								
	<b>41.60</b>	<b>8.67</b>				<b>48.00</b>		<b>120.00</b>	<b>30.41</b>				<b>135.88</b>		<b>78.40</b>	<b>188%</b>	<b>21.74</b>	<b>251%</b>	<b>87.88</b>	<b>183%</b>		
T1-S03-1	15.60	15.18				85.00	74.00	175.00	21.50				81.00	89.00								3/5
T1-S03-2	118.00	16.54				54.00	64.00															
T1-S03-4	158.00	15.01				60.00	56.00															
T1-S03-5	135.00	17.81				57.00	65.00															
	<b>106.65</b>	<b>16.14</b>				<b>64.38</b>		<b>175.00</b>	<b>21.50</b>				<b>85.00</b>		<b>68.35</b>	<b>64%</b>	<b>5.37</b>	<b>33%</b>	<b>20.63</b>	<b>32%</b>		
T1-S04-1	134.00	16.09				68.50	75.00	170.00	29.83				80.00	57.00								
T1-S04-2	122.00	13.73	4.98			43.50	48.50	135.00	44.30				64.00	60.00								

Figure 19: Automatic calculation of growth increases and number of deaths

## STEP 3

- The next step is selecting the Sheet titled Graph Tailings.



- This sheet constructs a graph for each of the tailings, with the different species on the x-axis and growth % on the y-axis, as illustrated by Figure 20 and Figure 21:

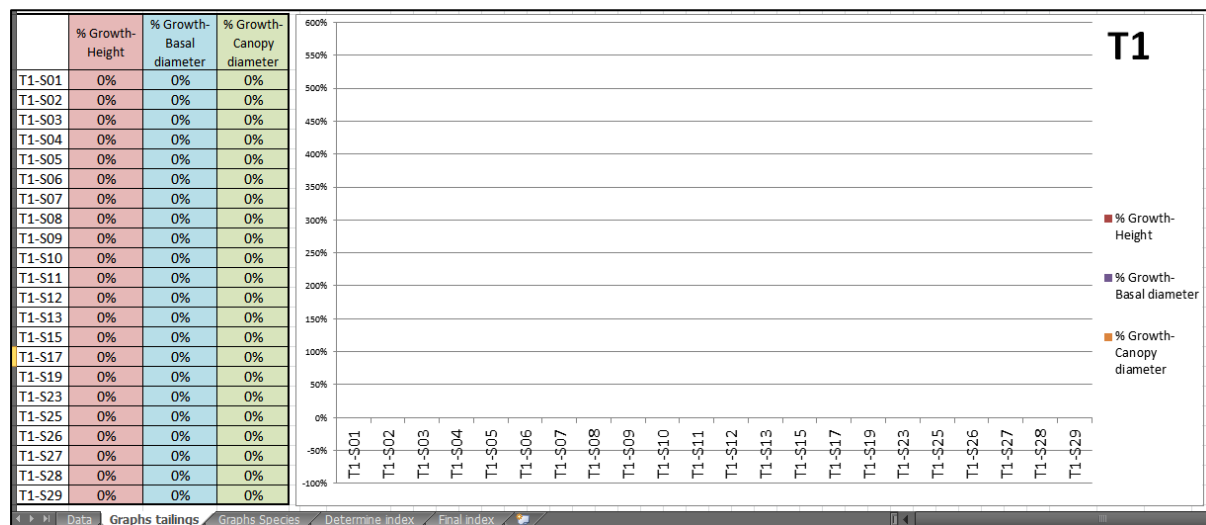


Figure 20: Tailings graph sheet before data is added

- After adding the data, graphs are automatically drawn up:

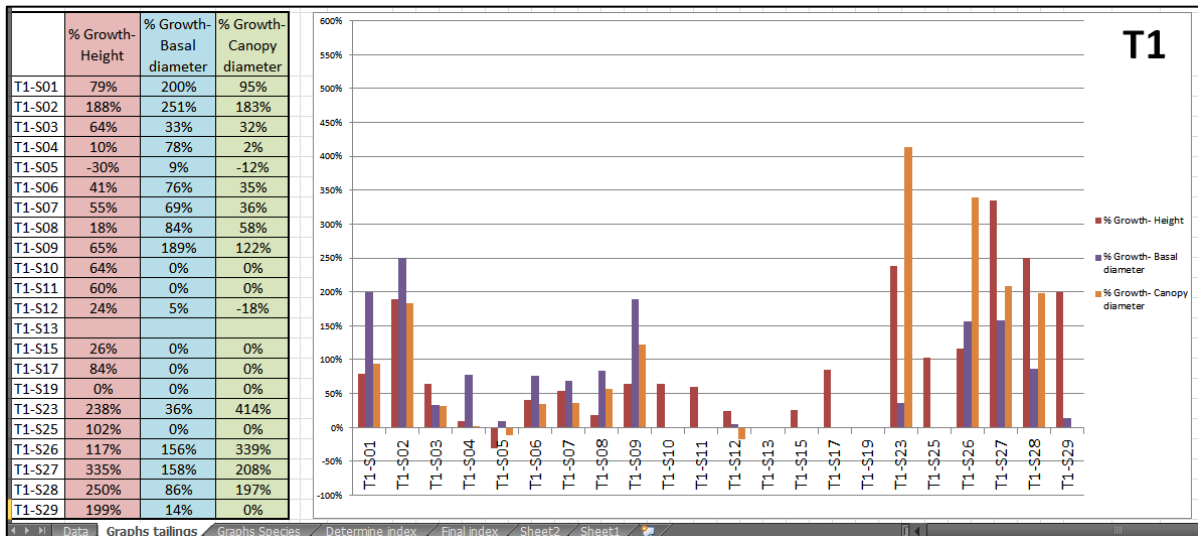


Figure 21: Tailings graph sheet after data is added

#### STEP 4

- This sheet constructs a graph for each species as shown by Figure 22 and Figure 23.
- This graph shows the different tailings on the x-axis and the growth percentage on the y-axis.
- This graph is significant because the growth of the species in each tailings can be compared to TC, the control soil.

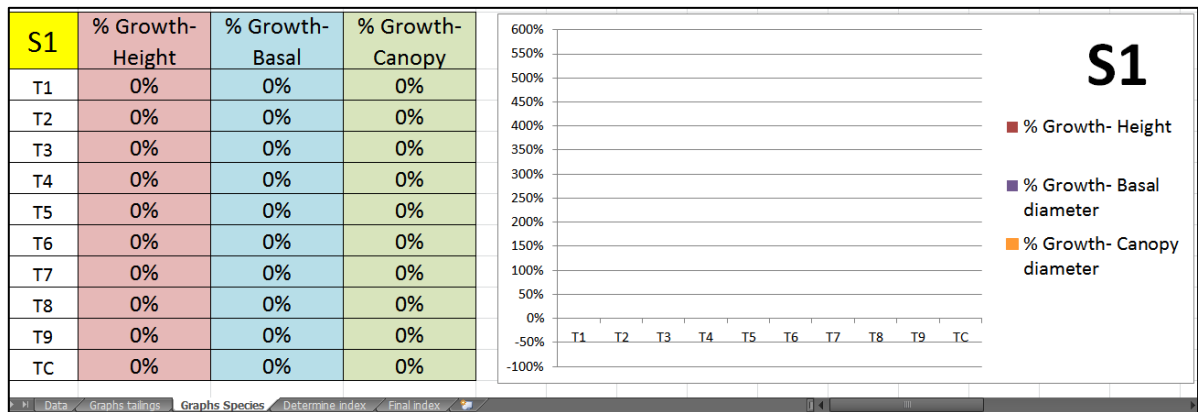


Figure 22: Species graph sheet before data is added

- After adding the data, the graph is automatically drawn up:

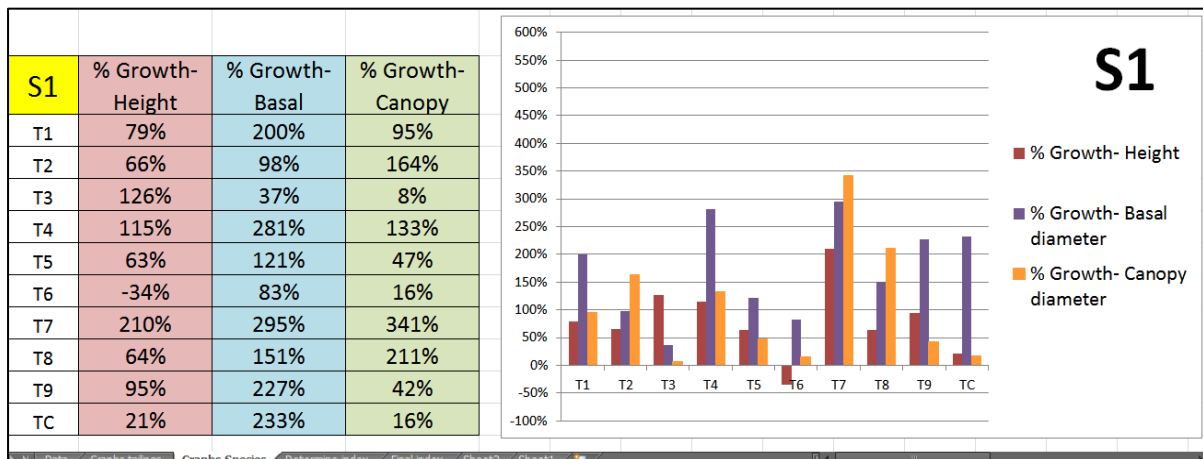


Figure 23: Species graph sheet after data is added

### STEP 5

- To use the growth percentages for the final index table, all the values are converted to a percentage out of 100% (Figure 24).
- This makes the allocation easier when the index is calculated.

		ORIGINAL PERCENTAGES			PROCESSED PERCENTAGES OUT OF 100%		
		% Growth- Height	% Growth- Basal diameter	% Growth- Canopy diameter	% Growth- Height	% Growth- Basal diameter	% Growth- Canopy diameter
3	T1-S01	79%	200%	95%	26%	43%	28%
4	T1-S02	188%	251%	183%	41%	50%	40%
5	T1-S03	64%	33%	32%	23%	19%	19%
6	T1-S04	10%	78%	2%	16%	25%	15%
7	T1-S05	-30%	9%	-12%	10%	16%	13%
8	T1-S06	41%	76%	35%	20%	25%	19%
9	T1-S07	55%	69%	36%	22%	24%	19%
10	T1-S08	18%	84%	58%	17%	26%	23%
11	T1-S09	65%	189%	122%	24%	41%	32%
12	T1-S10	64%	0%	0%	23%	0%	0%
13	T1-S11	60%	0%	0%	23%	0%	0%
14	T1-S12	24%	5%	-18%	18%	15%	12%
15	T1-S13						
16	T1-S15	26%	0%	0%	18%	0%	0%
17	T1-S17	84%	0%	0%	26%	0%	0%
18	T1-S19	0%	0%	0%	0%	0%	0%
19	T1-S23	238%	36%	414%	48%	19%	73%
20	T1-S25	102%	0%	0%	29%	0%	0%
21	T1-S26	117%	156%	339%	31%	37%	63%
22	T1-S27	335%	158%	208%	62%	37%	44%
23	T1-S28	250%	86%	197%	50%	27%	42%
24	T1-S29	199%	14%	0%	43%	16%	0%

Figure 24: Conversion of growth percentages for calculation of index

## STEP 6

- The index is calculated, as shown by Figure 25.
- The index is influenced by the weight that the height, canopy and basal diameter should count, as decided by the user. The weights are in percentages 0 – 100, therefore if all three are 100%, all three growth factors contribute equally.
- The formula takes into account the species that do not have a basal or canopy diameter i.e. basal and canopy diameter is considered negligible (grasses). In this case only height is used.
- It is also possible to insert a mortality factor which is multiplied with the fraction of failed/dead plant-tailings combinations which is then subtracted from the index e.g. if 1/5 of a certain combination failed and a factor of 2 is inserted, 1/5 is multiplied by 2 and subtracted from the score of that specific combination.

**The index is calculated by the following steps:**

	T1	T2	T3	T4	T5	T6	T7	T8	T9	TC	
S01	4.81	3.48	2.86	4.93	3.08	1.10	7.56	5.18	4.74	3.57	The values can be adjusted as required. Any number from 0 to 100 can be entered, which will be taken into account for the final award determinations.
S02	6.09	5.38	4.87	5.43	5.10	2.62	6.94	4.64	3.15	4.65	Percentage of the HEIGHT that must be used for the index
S03	1.57	2.15	1.93	2.62	2.87	-2.50	3.13	2.18	2.07	2.71	100%
S04	2.78	2.67	5.70	3.67	3.69	2.33	2.67	3.46	2.74	2.51	Percentage of the BASAL that must be used for the index
S05	0.40	1.28	2.08	0.07	1.09	1.88	2.38	1.10	1.99	2.43	100%
S06	3.23	3.06	2.62	2.98	3.13	2.26	2.88	3.15	2.69	3.27	Percentage of the CANOPY that must be used for the index
S07	3.28	3.99	4.50	3.91	2.79	2.73	4.30	2.31	4.64	3.53	100%
S08	3.28	1.54	1.95	2.72	2.54	-2.50	2.69	3.37	2.75	2.69	Mortality factor
S09	4.83	3.40	3.95	4.36	3.02	0.38	6.74	5.86	5.85	4.52	
S10	2.68	3.55	3.39	3.67	3.85	1.82	4.85	3.44	2.21	2.83	
S11	2.92	1.44	0.00	3.51	2.25	2.45	5.26	0.09	3.55	1.09	
S12	1.22	2.39	2.59	0.60	1.89	0.19	1.66	1.49	1.38	1.77	
S13	0.00	0.00	0.00	0.00	-2.50	2.62	4.80	1.65	2.88	2.14	
S15	2.70	1.65	1.38	2.41	3.08	0.58	5.40	1.39	3.07	-0.31	
S17	3.95	0.00	2.47	3.03	3.90	1.82	2.04	4.50	4.50	-2.50	
S19	2.40	5.11	3.42	1.83	2.96	1.29	8.51	2.56	1.92	1.37	
S23	6.64	4.46	8.18	8.21	7.94	7.72	6.72	4.99	4.18	4.41	
S25	3.50	5.39	4.29	5.03	3.12	5.51	3.01	3.71	3.07	4.14	
S26	5.89	2.36	3.88	6.06	4.74	4.06	4.77	4.75	6.44	9.38	
S27	7.15	5.81	-2.50	10.48	8.20	5.70	6.54	8.85	7.96	6.51	
S28	5.96	5.40	6.41	4.81	5.13	6.97	4.27	6.25	4.76	6.10	
S29	6.41	3.88	8.21	9.30	7.06	6.16	8.74	7.46	7.68	6.95	

Graphs Species Processed % Determine index Final index STDV and Average

Figure 25: Calculation of index table

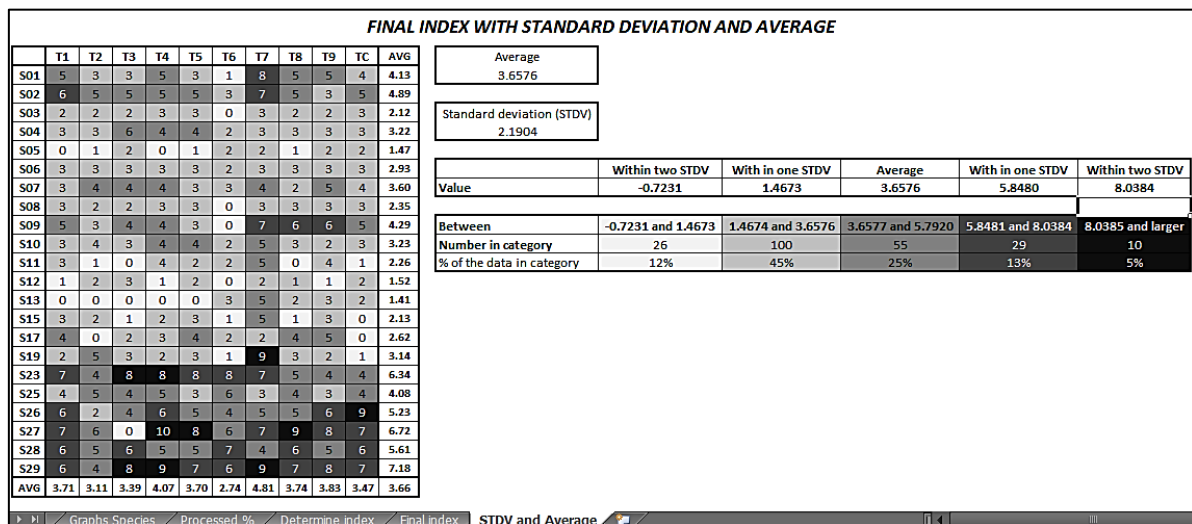
- The formula that determines the index number can be summarized by Table 9

Table 9: Summary of formula used to calculate index

Step	Description	Notes
1	Influence of height on index	<b>%Growth-Height X Weight % (Height)</b>
2	Influence of basal diameter on index	<b>%Growth-Basal X Weight % (Basal)</b>
3	Influence of canopy diameter on index	<b>%Growth-Canopy X Weight % (Canopy)</b>
4	Mortality factor:	<b>Fraction of dead/failed combinations X number chosen by user</b> This factor adjusts the index values negatively to account for failed combinations i.e. dead plants.

## STEP 7

- In this step, the index values are rounded off to the nearest integer and graded colours are used to indicate the success of the tailings-species combination.
- The averages are calculated with the original decimal scores that were calculated by the formula, not the rounded values.
- The table is subdivided, pairing the grass species together, and the tree species together.
- The standard deviation ( $\sigma$ ) is calculated, not only to measure the amount of variation from the average, but also to provide calculated values for grading the table instead of arbitrarily decided values. The grading system starts at [index value < avg. - 2 $\sigma$ ] in white, getting progressively darker towards [index value > avg. + 2 $\sigma$ ]. Therefore the darker cells are more successful than lighter cells. (Figure 26).
- In some cases a cell with a score higher than the average will have a lighter grading colour, the reason being that the program shades a cell according to its decimal value and not the value to which it has been rounded off.



**Figure 26: Calculation of standard deviation and colour grading according to index value  $>/<$  avg.  $\pm$   $\sigma$**

- The grass and tree species are separated and the standard deviation calculated for each index table (Figure 27 and Figure 28).
- The division of the index table into two tables containing the grasses and trees individually is significant to the standard deviation. The grass species are more comparable with one another, as is the case with the trees. This enables more accurate index tables.

GRASSES - FINAL INDEX WITH STANDARD DEVIATION AND AVERAGE												
	T1	T2	T3	T4	T5	T6	T7	T8	T9	TC	AVG	
S10	3	4	3	4	4	2	5	3	2	3	3.23	Average 3.2563
S11	3	1	0	4	2	2	5	0	4	1	2.26	
S13	0	0	0	0	0	3	5	2	3	2	1.41	Standard deviation (STDV) 2.2492
S15	3	2	1	2	3	1	5	1	3	0	2.13	
S17	4	0	2	3	4	2	2	4	5	0	2.62	
S19	2	5	3	2	3	1	9	3	2	1	3.14	
S25	4	5	4	5	3	6	3	4	3	4	4.08	
S29	6	4	8	9	7	6	9	7	8	7	7.18	
AVG	3.07	2.63	2.89	3.60	3.28	2.78	5.33	3.10	3.61	2.28	3.26	

	Within two STDV	With in one STDV	Average	With in one STDV	Within two STDV
Value	-1.2421	1.0071	3.2563	5.5054	7.7546

Between	-1.2421 and 1.0071	1.0072 and 3.2563	3.2564 and 5.5054	5.5055 and 7.7546	7.7547 and larger
Number in category	11	34	24	7	4
% of the data in category	14%	43%	30%	9%	5%

Graphs Species Processed % Determine index Final index STDV and Average

Figure 27: Index table of grasses with standard deviation

TREES - FINAL INDEX WITH STANDARD DEVIATION AND AVERAGE												
	T1	T2	T3	T4	T5	T6	T7	T8	T9	TC	AVG	
S01	5	3	3	5	3	1	8	5	5	4	4.13	Average 3.8870
S02	6	5	5	5	5	3	7	5	3	5	4.89	
S03	2	2	2	3	3	0	3	2	2	3	2.12	Standard deviation (STDV) 2.1303
S04	3	3	6	4	4	2	3	3	3	3	3.22	
S05	0	1	2	0	1	2	2	1	2	2	1.47	
S06	3	3	3	3	3	2	3	3	3	3	2.93	
S07	3	4	4	4	3	3	4	2	5	4	3.60	
S08	3	2	2	3	3	0	3	3	3	3	2.35	
S09	5	3	4	4	3	0	7	6	6	5	4.29	
S12	1	2	3	1	2	0	2	1	1	2	1.52	
S23	7	4	8	8	8	8	7	5	4	4	6.34	
S26	6	2	4	6	5	4	5	5	6	9	5.23	
S27	7	6	0	10	8	6	7	9	8	7	6.72	
S28	6	5	6	5	5	7	4	6	5	6	5.61	
AVG	4.08	3.38	3.68	4.34	3.94	2.71	4.52	4.11	3.95	4.15	3.89	

	Within two STDV	With in one STDV	Average	With in one STDV	Within two STDV
Value	-0.3735	1.7567	3.8870	6.0173	8.1476

Between	-0.3735 and 1.7567	1.7568 and 3.8870	3.8871 and 6.0173	6.0174 and 8.1476	8.1476 and larger
Number in category	18	59	39	18	6
% of the data in category	13%	42%	28%	13%	4%

Graphs Species Processed % Determine index Final index STDV and Average

Figure 28: Index table of trees with standard deviation

### 3.4 Liming and fertilization

#### 3.4.1 Acidification potential and Ca:Mg ratio

Liming requirements were based on soil chemical test results with regards to acidification potential, given in Table 10.

**Table 10: Acidification potential results before amelioration**

Sample no	pH (KCl)	pH (H <sub>2</sub> O)	Neutr pot	Titr acid	Acid pot 1	Nett acid pot
			ton/ha	ton/ha lime	ton/ha lime	ton/ha lime
T1	4.1	3.9	0	5	0	5
T2	5.3	5.4	0	4	11	15
T3	6.4	6.1	0	1	115	116
T4	8.0	6.6	34	0	2	-32
T5	7.6	9.7	121	0	0	-121
T6	2.3	2.4	0	76	92	168
T7	7.9	5.7	179	0	40	-139
T8	5.5	6.0	0	3	0	3
T9	3.8	2.5	0	103	152	255
TC	4.1	4.1	0	6	0	6

Table 11 shows the concentrations of Mg and Ca for each of the tailings. The last column that has been included is the calculated Ca:Mg ratios of each one of the materials. This is used to determine the type of lime that was used (calcitic or dolomitic).

**Table 11: Ca and Mg concentrations, as well as calculated Ca:Mg ratios**

Sample no	Ca	Mg	Ca: Mg
	mg kg <sup>-1</sup>	mg kg <sup>-1</sup>	ratio
T1	5595	17	197:1
T2	1793	94	12:1
T3	2043	261	5:1
T4	393	49	5:1
T5	1951	234	5:1
T6	1324	156	5:1
T7	2023	160	8:1
T8	392	406	1:2
T9	2237	211	6:1
TC	88	49	1:1

Figure 29 (FSSA, 2007:47) illustrates the system used to differentiate between the use of calcitic and dolomitic lime.

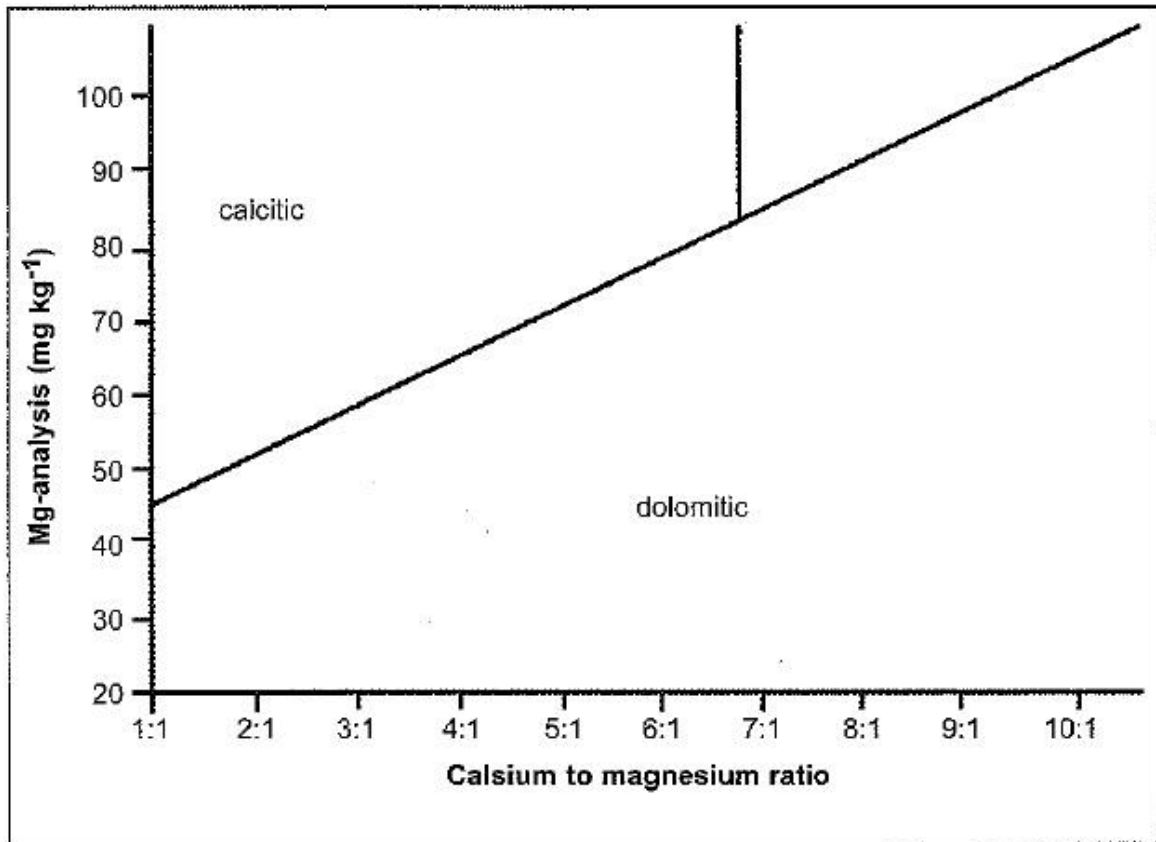


Figure 29: FSSA system for differentiating between use of calcitic or dolomitic lime

### 3.4.2 Major cations and anions

The concentrations of some major cations and anions are given by Table 12.

**Table 12: Major cations and anions**

Sample no	EC	P (Bray 1)	K	Ca	Mg	Na	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	NO <sub>3</sub> <sup>-</sup>	F <sup>-</sup>	HCO <sub>3</sub> <sup>-</sup>	Organic C	Total N
	mS.m <sup>-1</sup>	mg.kg <sup>-1</sup>	mg.kg <sup>-1</sup>	mg.kg <sup>-1</sup>	mg.kg <sup>-1</sup>	mg.kg <sup>-1</sup>	mg/L	mg/L	mg/L	mg/L	mg/L	%	%
T1	199	252	20	5595	17	12	6.6	1813.3	18	27.5	7.3	0.00	0.05
T2	193	1	30	1793	94	9	14.3	2186.9	13.8	0.1	65.9	0.00	0.04
T3	422	0	45	2043	261	117	100.7	3808.2	168.6	0.1	80.5	0.12	0.04
T4	205	0	31	393	49	68	549.4	1109.9	48.5	0	124.4	0.00	0.02
T5	121	5	720	1951	234	862	10.6	448.3	7.4	1.2	285.5	0.09	0.04
T6	1090	0	25	1324	156	22	7	114585	12.4	1.4	0	26.60	0.63
T7	146	1	24	2023	160	46	135	1574.9	1.7	14.9	153.7	12.05	0.04
T8	11	3	87	392	406	20	11	96.7	16	0.1	131.8	0.28	0.06
T9	390	1	25	2237	211	3	3	30340	13.3	0	0	54.34	1.28
TC	13	4	62	88	49	1	3.4	31.1	48.8	0	95.2	0.17	0.05

The concentrations of these cations were used to do the fertilization, liming and compost recommendation.

The following liming and fertilization recommendations were made (Geolab) based on the acidification potential, Ca: Mg ratio and major cations and anions:

- T1: Broadcast 5 ton/ha dolomite lime six weeks before planting and work in 15-20cm.  
Broadcast 80 ton/ha compost four weeks before planting and work in 5-10cm.  
Broadcast 250 kg/ha 4:3:4(33) immediately before planting and work in 5cm.  
Topdress 200 kg/ha LAN six weeks after planting.
- T2: Broadcast 15 ton/ha dolomite lime six weeks before planting and work in 15-20cm.  
Broadcast 35 ton/ha compost four weeks before planting and work in 5-10cm.  
Broadcast 350 kg/ha 4:3:4(33) immediately before planting and work in 5cm.  
Broadcast 150 kg/ha Superphosphate with seeds  
Topdress 150 kg/ha LAN six weeks after planting.  
Broadcast 116 ton/ha dolomite lime six weeks before planting and work in 15-20cm.
- T3: Broadcast 55 ton/ha compost four weeks before planting and work in 5-10cm.  
Broadcast 350 kg/ha 4:3:4(33) immediately before planting and work in 5cm.  
Broadcast 150 kg/ha Superphosphate with seeds.  
Topdress 150 kg/ha LAN six weeks after planting.
- T4: Broadcast 35 ton/ha compost four weeks before planting and work in 5-10cm.  
Broadcast 350 kg/ha 4:3:4(33) immediately before planting and work in 5cm.  
Broadcast 150 kg/ha Superphosphate with seeds.  
Topdress 150 kg/ha LAN six weeks after planting.
- T5: Broadcast 35 ton/ha compost four weeks before planting and work in 5-10cm.  
Broadcast 250 kg/ha 3:2:0(25) immediately before planting and work in 5cm.  
Topdress 150 kg/ha LAN six weeks after planting.
- T6: Broadcast 168 ton/ha dolomite lime six weeks before planting and work in 15-20cm.  
Broadcast 65 ton/ha compost four weeks before planting and work in 5-10cm.  
Broadcast 350 kg/ha 4:3:4(33) immediately before planting and work in 5cm.  
Broadcast 150 kg/ha Superphosphate with seeds.  
Topdress 150 kg/ha LAN six weeks after planting.
- T7: Broadcast 45 ton/ha compost four weeks before planting and work in 5-10cm.  
Broadcast 350 kg/ha 4:3:4(33) immediately before planting and work in 5cm.  
Broadcast 150 kg/ha Superphosphate with seeds.  
Topdress 150 kg/ha LAN six weeks after planting.
- T8: Broadcast 3 ton/ha calcite lime six weeks before planting and work in 15-20cm.  
Broadcast 35 ton/ha compost four weeks before planting and work in 5-10cm.  
Broadcast 350 kg/ha 3:2:1(25) immediately before planting and work in 5cm.  
Broadcast 100 kg/ha Superphosphate with seeds.  
Topdress 150 kg/ha LAN six weeks after planting.
- T9: Broadcast 255 ton/ha dolomite lime six weeks before planting and work in 15-20cm.  
Broadcast 55 ton/ha compost four weeks before planting and work in 5-10cm.  
Broadcast 350 kg/ha 4:3:4(33) immediately before planting and work in 5cm.  
Broadcast 150 kg/ha Superphosphate with seeds.  
Topdress 150 kg/ha LAN six weeks after planting.
- TC: Broadcast 6 ton/ha dolomite lime six weeks before planting and work in 15-20cm.  
Broadcast 30 ton/ha compost four weeks before planting and work in 5-10cm.  
Broadcast 350 kg/ha 3:2:1(25) immediately before planting and work in 5cm.  
Broadcast 100 kg/ha Superphosphate with seeds.  
Topdress 150 kg/ha LAN six weeks after planting.

## 3.5 Soil physical tests and analyses

### 3.5.1 Particle size distribution

#### Equipment:

- i. Analytical balance: 100 g capacity, resolution  $\pm 0.01$  g.
- ii. Standard hydrometer.
- iii. Reciprocating horizontal mechanical shaker, capable of 180 oscillations per minute.
- iv. Sedimentation cylinder
- v. Shaker bottle 200 mL and cap (polypropylene or glass).

#### Reagents:

- i. Deionized water, ASTM Type I grade.
- ii. Amyl alcohol.
- iii. Sodium Hexametaphosphate (HMP), 5% dispersing solution. Dissolve 50.0 g Na-hexametaphosphate in 1.0 L.

#### Procedure:

- i. Weigh  $40.0 \pm 0.05$  g of air-dried soil pulverized to pass 10 mesh sieve ( $<2.0$ mm) into 200mL container. Determine oven dry soil moisture on a 2nd sample of soil.
- ii. Add 100 mL of HMP solution, cap and place on reciprocating horizontal shaker for sixteen (16) hours.
- iii. Quantitatively transfer the suspension to the sedimentation cylinder and add deionized water to bring to 1.0 L final volume.
- iv. Allow the suspension to equilibrate to room temperature for two (2) hours.
- v. Insert plunger and thoroughly mix contents, dislodging sediment from the bottom of the cylinder. Finish stirring with two or three smooth stokes. As an alternative mixing procedure stopper the cylinder and use end over end shaking for one (1) minute. Add 2 mL of amyl alcohol to the surface to suspensions covered in foam. Repeat the process and determine hydrometer reading on a blank solution and to the nearest  $\pm 0.5$  g L<sup>-1</sup> as "RC1".
- vi. Lower the hydrometer carefully into the suspension after thirty(30)second sand take a reading after forty (40) second sand record to the nearest  $\pm 0.5$  g L<sup>-1</sup> as "R sand".
- vii. Remove the hydrometer carefully, rinse and wipe dry.
- viii. After six (6) hours record temperature of the suspension to the nearest  $\pm 1$ oC. Using the temperature correction values in Table 1 determine the settling time for the 2.0  $\mu$ m size fraction. Based on time after initiation of settling, reinsert the hydrometer carefully and take a reading and record as "R clay" to the nearest  $\pm 0.5$  g L<sup>-1</sup>. Repeat the process determining hydrometer reading on a blank solution and record as "RC2" to the nearest  $\pm 0.5$  g L<sup>-1</sup>.

#### Calculations:

Report results to the nearest 0.1% content:

- I. Sand % =  $(\text{oven dry soil mass} - (R_{\text{sand}} - RC1)) / (\text{oven dry soil mass}) \times 100$
- II. Clay % =  $(R_{\text{clay}} - RC2) / (\text{oven dry soil mass}) \times 100$
- III. Silt % =  $100 - (\text{Sand \%} + \text{Clay \%})$

(Michigan State University, 2015)

### 3.5.3 Root penetration resistance.

The hand penetrometer is a micro-processor based penetrometer designed for simple operation by one person. The operation of the penetrometer is menu driven. The unit is simply designed to be carried onto the site, placed upright and for a penetration to be conducted. (Geotron Systems, 2005:1)

Accurate measurements are taken by simply pressing a key and turning the handle to force the rod into the ground and in most conditions a reading can be taken within two minutes. The readings are displayed onto the LCD screen directly, showing the depth in cm and the reading in kPa. The data is stored in the solid-state memory to be transferred onto a computer afterwards. (Geotron Systems, 2005:1)

The internal rechargeable battery provides sufficient power to operate the device throughout a normal survey day. (Geotron Systems, 2005:1)

For T1 to T4 and T9 the following procedure was used:

- i. The different tailings materials were placed in 2 ton industrial mega-bags for this analysis. This was done to provide a large enough surface to take several readings.
- ii. The tailings were saturated with water and the first reading was taken at field capacity.
- iii. Five readings were taken in each bag, up to a depth of 25 cm and the average of the five was used.
- iv. Together with the penetration resistance, samples were taken from each bag to determine the gravimetric moisture content of the material.
- v. This process was repeated once a week for five weeks, to be able to correlate the increase in penetration resistance with the decline in moisture content.

For T7 and T8 a different approach was used. The tailings were left to dry to permanent wilting point and the readings were then taken.

The coarse texture of T5 and T6 caused varying readings which were not included in the final results.

### 3.5.4 Surface crust strength ten days after irrigation.

This analysis is done to assess the propensity of each of the tailings materials to form surface crusts. The test is done using a hand held core strength penetrometer (Figure 30), which measures the resistance of the surface to penetration, in  $\text{kg/cm}^2$ . Ten different readings are taken between several samples to ensure that an accurate mean value can be obtained.



**Figure 30: Hand held core strength penetrometer.**

This analysis is not applied to T5 and T6 because the extremely coarse texture makes the physical testing process unviable.

Method:

- i. Use the core strength penetrometer to measure the surface core strength in  $\text{kg/cm}^2$
- ii. Take two readings per bag, in five bags of each tailings type. This yields ten readings for each tailings material and ensures an accurate mean value.

### **3.5.5 Soil gravimetric moisture contents at five weeks apart (water retention)**

The objective of this analysis is to determine the water content of each of the growth mediums at field capacity; therefore three days after the tailings were saturated with water. From this point on, water contents are determined weekly to be able to plot the regression on graphs, giving a visual indication of the water retention of each of the tailings. This analysis is not applied to T6 because the extremely coarse texture of the coal discard makes the physical testing process unviable.

Method:

- i. Ten bags per growth medium are filled with tailings and irrigated up to water saturation.
- ii. After three days (field capacity), a sample is taken from the first two bags (one from each bag) and mixed into an oven proof bowl. This step is repeated for each of the nine growth mediums.
- iii. The sample is weighed to give a total mass,  $M_t$ .
- iv. The sample is now oven dried.
- v. The dry mass,  $M_s$ , of the sample can now be weighed.
- vi. By subtracting  $M_s$  from  $M_t$  the mass of the water,  $M_w$ , is obtained.
- vii. The gravimetric water potential can now be calculated with the equation  $W = M_w/M_t \cdot 100$
- viii. This is to be repeated at the same time for the subsequent four weeks, each time sampling from the next two undisturbed bags.

### 3.5.6 Bulk density calculation

This analysis is done to get an indication of soil compaction. Bulk density is expressed in  $\text{g/cm}^3$ .

#### Method:

- i. A soil sample is taken from each of the different tailings.
- ii. The volume of the auger is calculated using  $V = (3.14) \cdot (R)^2 \cdot \text{Height}$ .
- iii. Three samples are taken from different bags to ensure a more trustworthy analysis.
- iv. Samples are oven dried and weighed to get  $M_s$ .
- v. The following formula is used to calculate the dry bulk density  $\rho_D$ :  $\rho_D = M_s/V_t$
- vi. Note  $V_t$  must be multiplied by three because three samples were taken with the auger.

## 3.6 Soil chemical tests and analyses

### 3.6.1 pH (KCl)

This method indicates the activity of hydrogen atoms in a soil suspension in  $1 \text{ mol dm}^{-3}$  KCl. Potassium chloride is used to mask variation in salt concentration resulting from fertilizer residues, irrigation water and microbial decomposition of organic material. A stable reading is obtained by using  $1 \text{ mol dm}^{-3}$  KCl. Hydrogen activity in  $1 \text{ mol dm}^{-3}$  KCl may be as much as 1 or 2 pH units lower or higher than that measured in water.

#### Method:

- i. The pH meter is calibrated at a constant temperature with a 4.01, 7.01 and 10.01 buffer solution respectively.
  - ii. Re-calibration is done hourly to compensate for drift.
  - iii. Place 10g dried soil ( $\leq 2\text{mm}$ ) in a glass beaker.
  - iv. Add  $25 \text{ cm}^3$  KCl solution ( $1 \text{ mol dm}^{-3}$ )
  - v. Stir the contents rapidly for 5 seconds with a glass rod.
  - vi. Stir again after 50 minutes and allow to stand for 10 minutes.
  - vii. Determine the pH with a calibrated pH meter.
- (The Non-Affiliated Soil Analysis Committee; 1990)

### 3.6.2 pH ( $\text{H}_2\text{O}$ )

This procedure determines the pH of a soil in a 1:2.5 soil/water ratio suspension on a mass basis. pH ( $\text{H}_2\text{O}$ ) was done on the original tailings samples taken from all bags with established plants in January and June of 2013 (plants were established in 2012).

#### Method:

- i. The pH meter is calibrated at a constant temperature with a 4.01, 7.01 and 10.01 buffer solution respectively.
- ii. Re-calibration is done hourly to compensate for drift.
- iii. Place 10g dried soil ( $\leq 2\text{mm}$ ) in a glass beaker.
- iv. Add  $25 \text{ cm}^3$  de-ionized water.

- v. Stir the contents rapidly for 5 seconds with a glass rod.
- vi. Stir again after 50 minutes and allow to stand for 10 minutes.
- vii. Determine the pH after 30 seconds with the Hanna HI 991300 pH multi-meter.

(The Non-Affiliated Soil Analysis Committee; 1990)

### 3.6.3 Electrical Conductivity (EC)

The Hanna HI 991300 pH/EC multi-meter, also used to measure the pH in 3.6.2 ( $pH H_2O$ ), was used to determine the EC values of the tailings samples simultaneously with the pH. Sample preparation was therefore the same as for 3.6.2. EC was done on samples of the original tailings. EC was also done on samples from all bags with established plants in January and June of 2013 (plants were established in 2012). A list of these results is included in Appendix B along with pH ( $H_2O$ ).

### 3.6.4 Cation exchange capacity and water soluble cations

An ammonium acetate solution ( $1 \text{ mol dm}^{-3}$ ) serves as extractant for and water soluble cations. The maximum exchange occurs within a few minutes.

#### Extraction procedure:

- i. Place 10 g air-dry,  $\leq 2\text{mm}$  soil in a  $100 \text{ cm}^3$  centrifuge tube, stopper and determine mass of tube and soil.
- ii. Add  $50 \text{ cm}^3$   $1 \text{ mol dm}^{-3}$  ammonium acetate solution and shake horizontally for 60 minutes.
- iii. Remove samples from shaker and leave overnight.
- iv. Centrifuge at 2000 to 5000 rpm to obtain a clear supernatant solution (about 10 minutes).
- v. Decant supernatant liquid as completely as possible into a  $100 \text{ cm}^3$  volumetric flask, without losing any soil.
- vi. Again add  $50 \text{ cm}^3$   $1 \text{ mol dm}^{-3}$  ammonium acetate solution to the soil and shake tubes well by hand to ensure that the soil has dispersed properly.
- vii. Place tubes on shaker for 30 minutes, centrifuge and decant clear solution into the same  $100 \text{ cm}^3$  volumetric flask. Make up to volume with ammonium acetate solution, filter and keep this solution for determination of Ca, Mg, Na and K (Solution A).
- viii. Add  $50 \text{ cm}^3$   $0.1 \text{ mol dm}^{-3}$  ammonium acetate solution to the soil in the centrifuge tube. Shake for 30 minutes ensuring that the soil has dispersed properly. Centrifuge as before. Decant clear supernatant solution into a plastic storing bottle for the determination of  $\text{NH}_4^+$  in the occluded solution (Solution B). Stopper centrifuge tube and determine mass of centrifuge tube plus soil and occluded solution.
- ix. Finally add  $50 \text{ cm}^3$  KCl solution ( $1 \text{ mol dm}^{-3}$ ) to the soil in the centrifuge tube, shake for 30 minutes as described, centrifuge and decant supernatant solution into a  $200 \text{ cm}^3$  volumetric flask. Repeat operation with a second aliquot of  $50 \text{ cm}^3$  of KCl solution, again ensuring that the soil has dispersed properly. Fill volumetric flask to volume with  $1 \text{ mol dm}^{-3}$  KCl solution (Solution C).

(The Non-Affiliated Soil Analysis Work Committee, 1990)

### To determine CEC:

- i. Add 10 cm<sup>3</sup> boric acid indicator solution to a 100 cm<sup>3</sup> Erlenmeyer flask marked to indicate a volume of 50 cm<sup>3</sup>.
  - ii. Place the flask under the exit of the condenser of the steam distillation apparatus.
  - iii. In separate distillations, pipette 5 cm<sup>3</sup> of ammonium acetate into a distillation flask.
  - iv. Increase the volume to about 20 cm<sup>3</sup> with de-ionized water. Add 1 teaspoon heavy MgO through a dry funnel into the bulb of the flask.
  - v. Connect the distillation flask without delay to the steam generator and distill to a volume of ± 50 cm<sup>3</sup> in the flask containing boric acid indicator.
  - vi. Stop distillation by opening the stopcock on the steam by-pass tube and then remove the distillation flask.
  - vii. Rinse the exit tube of the condenser.
  - viii. Determine the NH<sup>4+</sup> by titrating with 0.05 mol dm<sup>-3</sup> sulphuric acid.
  - ix. The colour change at the end point is from green to a permanent faint pink.
- (The Non-Affiliated Soil Analysis Work Committee, 1990)

### Calcium and Magnesium:

- i. Pipette 5 cm<sup>3</sup> ammonium acetate extract of the soil into a 200 cm<sup>3</sup> volumetric flask. Add 10 cm<sup>3</sup> La-solution and 10 cm<sup>3</sup> 6 mol dm<sup>-3</sup> HCl to dissolve any precipitate. Make up to volume with de-ionized water. Mix well and filter if necessary.
  - ii. Determine Ca and Mg on atomic absorption spectrophotometer.
- (The Non-Affiliated Soil Analysis Work Committee, 1990)

### Potassium and sodium:

- i. The wavelength of the spectral line used for determining potassium is 766.5 nm on the atomic absorption spectrophotometer.
  - ii. The most usable emission spectra for sodium analysis are the 589.0 and 589.6 nm lines. All alkali metals are easily excited by a flame. To reduce interference, a low flame is recommended.
  - iii. Alternatively a flame photometer can be used if the matrix of the sample and standards are matched.
- (The Non-Affiliated Soil Analysis Work Committee, 1990)

### CEC calculation:

$$\text{CEC} = (\mathbf{T}_1 \times 20) - (\mathbf{X}_2 - \mathbf{X}_1) \times 0.2 \times \mathbf{T}_2 \text{ cmol(+) kg}^{-1}$$

Where:  $\mathbf{T}_1$  = Titration value for KCl solution

$\mathbf{T}_2$  = Titration value for ammonium acetate solution

$\mathbf{X}_1$  = Mass of tube + soil (g)

$\mathbf{X}_2$  = Mass of tube + occluded solution (g)

(The Non-Affiliated Soil Analysis Work Committee, 1990)

### Calcium and Magnesium calculation:

10g soil is extracted with 100 cm<sup>3</sup> ammonium acetate solution and 5 cm<sup>3</sup> of this solution is subsequently diluted to 200 cm<sup>3</sup>.

Let Ca/Mg concentration in this solution be **s** mg dm<sup>-3</sup>.

$$\text{mg kg}^{-1} \text{ Ca/Mg in soil} = \frac{s \times 100 \times 40}{10} \text{ (g)}$$

(The Non-Affiliated Soil Analysis Work Committee, 1990)

### Potassium and sodium calculation:

10 g soil is extracted with 100 cm<sup>3</sup> extractant. Let Na/K concentration of the extractant be **n** mg dm<sup>-3</sup>.

$$\text{mg kg}^{-1} \text{ in soil} = \frac{n \times 100}{10} \text{ (g)}$$

### Cations

Let concentration in original solution be **a** mg dm<sup>-3</sup>, then:

$$\begin{aligned} \text{cmol(+) kg}^{-1} \text{Ca} &= \frac{a}{20.04} \\ \text{cmol(+) kg}^{-1} \text{Mg} &= \frac{a}{1216} \\ \text{cmol(+) kg}^{-1} \text{K} &= \frac{a}{39.10} \\ \text{cmol(+) kg}^{-1} \text{Na} &= \frac{a}{22.99} \end{aligned}$$

(The Non-Affiliated Soil Analysis Committee; 1990)

### **3.6.5 Extractable phosphorus: Bray-1**

A known mass of soil is shaken with Bray-1 solution. Contact time between soil and extractant should not exceed 60 seconds. This procedure extracts the more soluble phosphorus and is of most significance when analyzing cultivated soils.

#### Extraction procedure at 20 ± 2°C

- i. Place 6.67 g soil (≤ 2mm) in an extraction bottle.
- ii. Add 50 cm<sup>3</sup> Bray-1 solution (20°C).
- iii. Stopper the bottle and shake contents manually (up and down) for 60 seconds.
- iv. Add 2 drops flocculant.
- v. Filter immediately through Whatman no 2 filter paper into a suitable bottle.

#### Determination:

The P concentration of the extracts is determined against the standards solutions using a continuous flow analyser.

### Calculation:

Let concentration of phosphorus as read from the calibration curve be  $q$  mg dm<sup>-3</sup>.

$$\text{mg kg}^{-1} \text{ P in soil} = \frac{q \times 50}{6.68} \text{ (g)}$$

(The Non-Affiliated Soil Analysis Committee; 1990)

### **3.6.6 Organic carbon: Walkley-Black**

Organic material in soil may be oxidized by treatment of a hot mixture of K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> and sulphuric acid, according to the reaction:

After completion of the reaction, the excess dichromate is titrated with iron(II) ammonium sulphate hexahydrate. The reduced dichromate is assumed to be equivalent to the organic C present in the sample, assuming that soil organic matter has an average valence of zero.

### Method:

- i. Standardize the iron(II) ammonium sulphate solution daily against 10 cm<sup>3</sup> 0.167 mol dm<sup>-3</sup> K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> as described below.
- ii. Grind the soil to pass a 0.35 mm sieve, using a porcelain mortar and pestle.
- iii. Transfer 1 g air dry soil to a 500 cm<sup>3</sup> Erlenmeyer flask. Add 10 cm<sup>3</sup> K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> solution by pipette to the soil sample.
- iv. Swirl the flask to disperse the soil in the solution. Rapidly add 20 cm<sup>3</sup> concentrated sulphuric acid, directing the stream into the solution. Again swirl the flask gently until soil and reagents are mixed well and then more vigorous for a total time of 1 minute. Allow the flask to cool on a sheet of asbestos for 30 minutes.
- v. Add 150 cm<sup>3</sup> de-ionized water and 10 cm<sup>3</sup> concentrated ortho-phosphoric acid.
- vi. Add 1 cm<sup>3</sup> indicator and titrate excess dichromate with iron(II) ammonium sulphate solution. As the endpoint is approached, the solution colour changes to dark violet brown. Add iron(II) ammonium sulphate drop by drop until the colour changes sharply to green. Repeat the determination with less soil if more than 75% of the dichromate is reduced.

(The Non-Affiliated Soil Analysis Work Committee, 1990)

### Calculation:

Calculate the carbon content according to the following formula, using a recovery factor of  $f = 1.3$  or a more suitable value established experimentally.

Concentration of:

$$Fe(NH_4)_2(SO_4)_2 \text{ mol dm}^{-3} = (10 \text{ cm}^3 K_2Cr_2O_7) \times 0.167 \times 6 / \text{cm}^3 Fe(NH_4)_2(SO_4)_2$$

$$\text{Organic C\%} = \frac{[\text{cm}^3 Fe(NH_4)_2(SO_4)_2 \text{ blank} - \text{cm}^3 Fe(NH_4)_2(SO_4)_2 \text{ sample}] \times M \times 0.3}{\times f / \text{soil mass (g)}}$$

Where  $M$  = Concentration of the  $Fe(NH_4)_2(SO_4)_2$  in mol dm<sup>-3</sup>

(The Non-Affiliated Soil Analysis Committee; 1990).

## Chapter 4 - Results and Discussion

### 4.1 Soil physical tests and analyses summary

The most significant results of the physical baseline study done on the tailings are summarized in Table 13.

**Table 13: Table summarizing soil physical analyses and results**

Tailings	Soil physical parameter	Result	Comments/Implications
T1	• Particle Size Distribution	• Very fine sand: 77% Silt: 15% Clay: 7% Other: 1%	• Material is loosely packed; no density compaction
	• Water Infiltration Capacity	• 181 mm/h	• High. Macropores act as water conduits, i.e. water can infiltrate easily
	• Water Retention (Gravimetric moisture content over 5 weeks)	• Week 1: 33% Week 2: 29% Week 3: 22% Week 4: 15% Week 5: 12%  % of initial moisture retained: 36%	• Hygroscopic water retention
	• Surface crust density	• 0.955 kg.cm <sup>2</sup>	• Low; not prone to dense crust formation
	• Bulk density	• 0.81 g.cm <sup>3</sup>	• Very low bulk density (Hazelton & Murphy, 2007:20); no compaction; loosely packed material.
T2	• Particle Size Distribution	• Varies from fine sand to silt	• Dense compaction of material occurs.
	• Water Infiltration Capacity	• 21.1 mm/h	• Normal infiltration rate for sandy loam texture (FAO, 2014).
	• Water Retention (Gravimetric moisture content over 5 weeks)	• Week 1: 12% Week 2: 9% Week 3: 5% Week 4: 5% Week 5: 2%  % of initial moisture	• Low water retention; prone to crust formation when dry.

	<ul style="list-style-type: none"> <li>• Surface crust density</li> <li>• Bulk density</li> </ul>	<p>retained: 16.6%</p> <ul style="list-style-type: none"> <li>• 1.305 kg.cm<sup>2</sup></li> <li>• 1.28 g.cm<sup>3</sup></li> </ul>	<ul style="list-style-type: none"> <li>• Dense surface crust formation.</li> <li>• Low density (Hazelton &amp; Murphy, 2007:20)</li> </ul>
T3	<ul style="list-style-type: none"> <li>• Particle Size Distribution</li> <li>• Water Infiltration Capacity</li> <li>• Water Retention (Gravimetric moisture content over 5 weeks)</li> <li>• Surface crust density</li> <li>• Bulk density</li> </ul>	<ul style="list-style-type: none"> <li>• Varies from fine sand to silt.</li> <li>• 18.3 mm/h</li> <li>• Week 1: 19% Week 2: 8% Week 3: 6% Week 4: 5% Week 5: 2%</li> <li>• % of initial moisture retained: 10.5%</li> <li>• 1.17 kg.cm<sup>2</sup></li> <li>• 1.36 g.cm<sup>3</sup></li> </ul>	<ul style="list-style-type: none"> <li>• Dense compaction of material occurs.</li> <li>• Normal rate for loam texture (FAO, 2014).</li> <li>• Low water retention.</li> <li>• Less prone to crust formation than gold tailings T2.</li> <li>• Moderate (Hazelton &amp; Murphy, 2007:20)</li> </ul>
T4	<ul style="list-style-type: none"> <li>• Particle Size Distribution</li> <li>• Water Infiltration Capacity</li> <li>• Water Retention (Gravimetric moisture content over 5 weeks)</li> <li>• Surface crust density</li> <li>• Bulk density</li> </ul>	<ul style="list-style-type: none"> <li>• Clay: 2% Silt: 7% Very fine sand: 34% Fine sand: 48% Medium sand: 9%</li> <li>• 41 mm/h</li> <li>• Week 1: 10% Week 2: 10% Week 3: 4% Week 4: 3% Week 5: 2%</li> <li>• % of initial moisture retained: 25.1%</li> <li>• 0.915 kg.cm<sup>2</sup></li> <li>• 1.76 g.cm<sup>3</sup></li> </ul>	<ul style="list-style-type: none"> <li>• Wider particle size distribution; low clay; high sand. Not very compacted.</li> <li>• High. Max value for sand texture is 30. (FAO, 2014)</li> <li>• Low initial moisture content; material loses moisture at rapid rate</li> <li>• Low; not prone to dense crust formation</li> <li>• High (Hazelton &amp; Murphy,</li> </ul>

			2007:20)
T5	<ul style="list-style-type: none"> <li>• Particle Size Distribution</li> <li>• Water Infiltration Capacity</li> <li>• Water Retention (Gravimetric moisture content over 5 weeks)</li> <li>• Surface crust density</li> <li>• Bulk density</li> </ul>	<ul style="list-style-type: none"> <li>• Very coarse sand: 35% Coarse sand: 33% Medium sand: 14% Fine sand: 8% Very fine sand – clay: 10%</li> <li>• 961 mm/h</li> <li>• Week 1: 7% Week2: 5.32% Week 3: 4.71% Week 4: 4.34% Week5: 4.17%  % of initial moisture retained: 66%</li> <li>• N/A</li> <li>• 1.56 g.cm<sup>3</sup></li> </ul>	<ul style="list-style-type: none"> <li>• Coarse texture; loosely packed material.</li> <li>• Due to coarse texture of material and material being loosely packed a high volume of macro-pores act as quick conduits for water.</li> <li>• Very low porosity ie. initial moisture is very low. Retention appears high due to final and initial values not differing much.</li> <li>• No surface crusting; very coarse and loosely packed material.</li> <li>• Moderate. (Hazleton &amp; Murphy, 2007:20)</li> </ul>
T6	<ul style="list-style-type: none"> <li>• Particle Size Distribution</li> <li>• Water Infiltration Capacity</li> <li>• Water Retention (Gravimetric moisture content over 5 weeks)</li> </ul>	<ul style="list-style-type: none"> <li>• Medium sand - very coarse sand: 79% Fine sand: 11% Very fine sand – clay: 10%. Also contains pebbles and cobbles.</li> <li>• N/A</li> <li>• Week 1: 22% Week 2: 16% Week 3: 11% Week 4: 10% Week 5: 4%  % of initial moisture retained: 18%.</li> </ul>	<ul style="list-style-type: none"> <li>• Very coarse texture; material is loosely packed.</li> <li>• Method not applicable due to texture.</li> <li>• This particular analysis was done on T6 and T9 mixed tailings which explain the unexpected high values.</li> </ul>

	<ul style="list-style-type: none"> <li>• Surface crust density.</li> <li>• Bulk density</li> </ul>	<ul style="list-style-type: none"> <li>• N/A</li> <li>• 1.21 g.cm<sup>3</sup></li> </ul>	<ul style="list-style-type: none"> <li>• Method not applicable due to texture; material is loosely packed- no crusting expected.</li> <li>• Low. (Hazelton &amp; Murphy, 2007:20)</li> </ul>
T7	<ul style="list-style-type: none"> <li>• Particle Size Distribution</li> <li>• Water Infiltration Capacity</li> <li>• Water Retention (Gravimetric moisture content over 5 weeks)</li> <li>• Surface crust density</li> <li>• Bulk density</li> </ul>	<ul style="list-style-type: none"> <li>• Very fine sand: 31% Fine sand: 36% Medium sand: 16% Silt: 12% Other: 5%</li> <li>• 17.2 mm/h</li> <li>• Week 1: 13% Week 2: 10% Week 3: 7% Week 4: 6% Week 5: 3%</li> <li>• % of initial moisture retained: 25%</li> <li>• 2.25 kg.cm<sup>2</sup></li> <li>• 1.51 g.cm<sup>3</sup></li> </ul>	<ul style="list-style-type: none"> <li>• Dense compaction; hard setting when dewatered.</li> <li>• Normal rate for loam texture (FAO, 2014).</li> <li>• Low initial moisture content; material loses moisture at rapid rate.</li> <li>• Very dense surface crust formation.</li> <li>• Moderate (Hazelton &amp; Murphy, 2007:20)</li> </ul>
T8	<ul style="list-style-type: none"> <li>• Particle Size Distribution</li> <li>• Water Infiltration Capacity</li> <li>• Water Retention (Gravimetric moisture content over 5 weeks)</li> <li>• Surface crust density</li> </ul>	<ul style="list-style-type: none"> <li>• Silt: 69% Clay: 15% Other: 16%</li> <li>• 19.5 mm/h</li> <li>• Week 1: 19% Week 2: 16% Week 3: 14% Week 4: 10% Week 5: 6%</li> <li>• % of initial moisture retained: 34%</li> <li>• 2.281 kg.cm<sup>2</sup></li> </ul>	<ul style="list-style-type: none"> <li>• Prone to extreme hard setting when dry.</li> <li>• Normal rate for loam texture (FAO, 2014)</li> <li>• High water retention; material stays wet for long.</li> <li>• Extreme hard setting when dry.</li> </ul>

	<ul style="list-style-type: none"> <li>• Bulk density</li> </ul>	<ul style="list-style-type: none"> <li>• 1.08 g.cm<sup>3</sup></li> </ul>	<ul style="list-style-type: none"> <li>• Low. (Hazelton &amp; Murphy, 2007:20)</li> </ul>
T9	<ul style="list-style-type: none"> <li>• Particle Size Distribution</li> <li>• Water Infiltration Capacity</li> <li>• Water Retention (Gravimetric moisture content over 5 weeks)</li> <li>• Surface crust density</li> <li>• Bulk density</li> </ul>	<ul style="list-style-type: none"> <li>• Nearly equal parts medium sand to clay.</li> <li>• 27.4 mm/h</li> <li>• Week 1: 31% Week 2: 28% Week 3: 24% Week 4: 18% Week 5: 13%</li> <li>• % of initial moisture retained: 42%</li> <li>• 2.34 kg.cm<sup>2</sup></li> <li>• 0.83 g.cm<sup>3</sup></li> </ul>	<ul style="list-style-type: none"> <li>• Wider particle size distribution than other tailings; extreme hard setting and surface crust formation was observed.</li> <li>• Normal rate for sandy loam texture (FAO, 2014).</li> <li>• High water retention; material stays wet for long.</li> <li>• Extreme hard setting and crust formation when dewatered.</li> <li>• Low. (Hazelton &amp; Murphy, 2007:20)</li> </ul>
TC	<ul style="list-style-type: none"> <li>• Particle Size Distribution</li> <li>• Water Infiltration Capacity</li> <li>• Water Retention (Gravimetric moisture content over 5 weeks)</li> <li>• Surface crust density</li> </ul>	<ul style="list-style-type: none"> <li>• Medium sand – very fine sand: 87% Silt: 3% Clay: 4% Other: 6%</li> <li>• 58 mm/h</li> <li>• Week 1: 11% Week 2: 8% Week 3: 6% Week 4: 5% Week 5: 4%</li> <li>• % of initial moisture retained: 39%</li> <li>• 1.1 kg.cm<sup>2</sup></li> </ul>	<ul style="list-style-type: none"> <li>• Typical particle size distribution of a sandy loam; some signs of crust formation.</li> <li>• High. Max value for sand texture according to FAO, (2014) is 30.</li> <li>• Low initial moisture content; Quick to dry.</li> <li>• Minor surface crust formation observed.</li> </ul>

	<ul style="list-style-type: none"> <li>• Bulk density</li> </ul>	<ul style="list-style-type: none"> <li>• 1.51 g.cm<sup>3</sup></li> </ul>	<ul style="list-style-type: none"> <li>• Moderate (Hazelton &amp; Murphy, 2007:20)</li> </ul>
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#### 4.1.1 Discussion of physical analyses

The gypsum tailings (T1), although remaining loosely packed, forms laminar plate structures in the potting bags after cycles of being watered and left to dry. The plate structures are too dense for roots to penetrate and roots have to develop along cracks and cavities in and between the structures. This was however negligible in this particular study, as the root systems of the seedlings were already adequate to survive when they were planted in the tailings. A second negative characteristic was that although the water retention of T1 is high compared to the other tailings and the control, this is mainly due to hygroscopic water retention, making it unavailable for plant use. The effect of this was not visible in the plants, as they were irrigated regularly as would be the case when rehabilitating a TSF.

Both the gold tailings (T2 and T3) displayed similar negative physical characteristics. Because of the lack of textural variation in the material, compaction of the material occurs making it difficult for plant root development. Crust formation on the surface of the tailings results in restriction of shoots, where seeds are planted for rehabilitation. The moisture retention of both gold tailings was observed to be very low, indicating that without irrigation in the initial phase of rehabilitation most plants will not survive.

The particle size of the platinum tailings (T4) was larger, compared to the gold; clay size particles were only 2% whilst the very fine to medium sand fraction was collectively 81%. This makes the material not prone to compaction; however the bulk density is high due to the heavy mafic minerals that make up the material. The platinum tailings had weak structure and low water retention, making frequent irrigation necessary for plants to survive.

The coarse kimberlite (T5) and the coarse coal tailings (T6) proved to be the most difficult mediums to rehabilitate due to the physical characteristics thereof. Because the textures of both tailings are mostly coarse sand and gravel, it does not have adequate structure to support plant roots and retains very little water. Plants in these materials exhibited signs of water stress. Furthermore, pieces of solid rock obstructed plant roots.

The fluorspar tailings (T7) are also prone to compact densely inside the potting bags, as in the case of the gold tailings. The material also forms dense crusts when dewatered.

The andalusite tailings (T8) had a texture of mainly clay and silt particles. Although the material had higher moisture retention than most of the other tailings, it was prone to extreme hardening when dried. Hardening starts at the surface layer and thickens as the material loses moisture. The resulting crust becomes too hard to penetrate with a metal spike. The fine coal tailings (T9) are also prone to extreme hardening and surface crust formation when dewatered.

The control soil (TC) was ameliorated to improve texture and nutrient deficiencies, but did not display specific negative extremes regarding physical characteristics.

## 4.2 Soil chemical tests and analyses summary

The most significant results of the chemical baseline study done on the tailings are summarized in Table 14.

**Table 14: Table summarizing chemical analyses and results**

Tailings	Soil chemical parameter	Result	Comments/Implications
T1	<ul style="list-style-type: none"> <li>pH (KCl)</li> <li>pH (H<sub>2</sub>O)</li> <li>Al</li> </ul>	<ul style="list-style-type: none"> <li>4.1</li> <li>3.9</li> <li>0.62 cmol.kg<sup>-1</sup></li> </ul>	<ul style="list-style-type: none"> <li>Acidic; Al toxicity possible; ameliorated with dolomitic lime (Ca:Mg ratio of 197:1).</li> </ul>
	<ul style="list-style-type: none"> <li>EC</li> <li>ESP</li> </ul>	<ul style="list-style-type: none"> <li>199 mS.m<sup>-1</sup></li> <li>22.19%</li> </ul>	<ul style="list-style-type: none"> <li>High sodicity. Flocculating agents used to separate impurities from gypsum ore during the crushing process (sodium lauryl sulphate and sodium oleyl sulphate), result in sodicity of the tailings.</li> </ul>
	<ul style="list-style-type: none"> <li>CEC</li> </ul>	<ul style="list-style-type: none"> <li>0.2 cmol.kg<sup>-1</sup></li> </ul>	<ul style="list-style-type: none"> <li>Very low; ameliorated with compost.</li> </ul>
	<ul style="list-style-type: none"> <li>Organic C%</li> <li>Total N%</li> </ul>	<ul style="list-style-type: none"> <li>0</li> <li>0.05</li> </ul>	<ul style="list-style-type: none"> <li>Very low; C/N ratio unfavourable; ameliorated with fertilizer and compost.</li> </ul>
T2	<ul style="list-style-type: none"> <li>pH (KCl)</li> <li>pH (H<sub>2</sub>O)</li> <li>Al</li> </ul>	<ul style="list-style-type: none"> <li>5.3</li> <li>5.4</li> <li>0.04 cmol.kg<sup>-1</sup></li> </ul>	<ul style="list-style-type: none"> <li>Acidic; ameliorated with dolomitic lime (Ca:Mg ratio of 12:1).</li> </ul>
	<ul style="list-style-type: none"> <li>EC</li> <li>ESP</li> </ul>	<ul style="list-style-type: none"> <li>193 mS.m<sup>-1</sup></li> <li>3.11%</li> </ul>	<ul style="list-style-type: none"> <li>Lower than criteria for saline and sodic.</li> </ul>
	<ul style="list-style-type: none"> <li>CEC</li> </ul>	<ul style="list-style-type: none"> <li>1.3 cmol.kg<sup>-1</sup></li> </ul>	<ul style="list-style-type: none"> <li>Very low; ameliorated with compost.</li> </ul>
	<ul style="list-style-type: none"> <li>Organic C%</li> <li>Total N%</li> </ul>	<ul style="list-style-type: none"> <li>0</li> <li>0.04</li> </ul>	<ul style="list-style-type: none"> <li>Very low; C/N ratio unfavourable; ameliorated with fertilizer and compost.</li> </ul>

T3	<ul style="list-style-type: none"> <li>• pH (KCl)</li> <li>• pH (H<sub>2</sub>O)</li> <li>• Al</li> <li>• EC</li> <li>• ESP</li> <li>• CEC</li> <li>• Organic C%</li> <li>• Total N%</li> </ul>	<ul style="list-style-type: none"> <li>• 6.4</li> <li>• 6.1</li> <li>• 0 cmol.kg<sup>-1</sup></li> <li>• 422 mS.m<sup>-1</sup></li> <li>• 61.05%</li> <li>• 0.8 cmol.kg<sup>-1</sup></li> <li>• 0.12</li> <li>• 0.04</li> </ul>	<ul style="list-style-type: none"> <li>• Slightly acidic.</li> <li>• High salinity and sodicity. High So<sub>4</sub><sup>2-</sup> content: 3808 mg/L</li> <li>• Very low; ameliorated with compost.</li> <li>• Very low; C/N ratio unfavourable; ameliorated with lime and compost.</li> </ul>
T4	<ul style="list-style-type: none"> <li>• pH (KCl)</li> <li>• pH (H<sub>2</sub>O)</li> <li>• Al</li> <li>• EC</li> <li>• ESP</li> <li>• CEC</li> <li>• Organic C%</li> <li>• Total N%</li> </ul>	<ul style="list-style-type: none"> <li>• 8</li> <li>• 6.6</li> <li>• 0 cmol.kg<sup>-1</sup></li> <li>• 205 mS.m<sup>-1</sup></li> <li>• 24.94%</li> <li>• 1.2 cmol.kg<sup>-1</sup></li> <li>• 0</li> <li>• 0.02</li> </ul>	<ul style="list-style-type: none"> <li>• High alkalinity (HCO<sub>3</sub> = 124.4 mg/l).</li> <li>• High sodicity.</li> <li>• Low; ameliorated with compost.</li> <li>• Very low; unfavourable C/N ratio; ameliorated with compost fertilizer.</li> </ul>
T5	<ul style="list-style-type: none"> <li>• pH (KCl)</li> <li>• pH (H<sub>2</sub>O)</li> <li>• Al</li> <li>• EC</li> <li>• ESP</li> <li>• CEC</li> <li>• Organic C%</li> <li>• Total N%</li> </ul>	<ul style="list-style-type: none"> <li>• 7.6</li> <li>• 9.7</li> <li>• 0 cmol.kg<sup>-1</sup></li> <li>• 121 mS.m<sup>-1</sup></li> <li>• 39.35%</li> <li>• 9.5 cmol.kg<sup>-1</sup></li> <li>• 0.09</li> <li>• 0.04</li> </ul>	<ul style="list-style-type: none"> <li>• Alkaline.</li> <li>• High sodicity.</li> <li>• Good.</li> <li>• Very low; unfavourable C/N ratio; ameliorated with compost and fertilizer.</li> </ul>

T6	<ul style="list-style-type: none"> <li>pH (KCl)</li> <li>pH (H<sub>2</sub>O)</li> <li>Al</li> <li>EC</li> <li>ESP</li> <li>CEC</li> <li>Organic C%</li> <li>Total N%</li> </ul>	<ul style="list-style-type: none"> <li>2.3</li> <li>2.4</li> <li>9.15 cmol.kg<sup>-1</sup></li> <li>1090 mS.m<sup>-1</sup></li> <li>15.33%</li> <li>0.6 cmol.kg<sup>-1</sup></li> <li>26.60</li> <li>0.63</li> </ul>	<ul style="list-style-type: none"> <li>Extremely acidic; aluminium toxicity; ameliorated with dolomitic lime (Ca:Mg ratio of 5:1).</li> <li>Extremely saline. High SO<sub>4</sub><sup>2-</sup> content: 114 585 mg/L</li> <li>Very low; ameliorated with compost.</li> <li>High carbon due to coal; low N; C/N ratio unfavourable; ameliorated with fertilizer.</li> </ul>
T7	<ul style="list-style-type: none"> <li>pH (KCl)</li> <li>pH (H<sub>2</sub>O)</li> <li>Al</li> <li>EC</li> <li>ESP</li> <li>CEC</li> <li>Organic C%</li> <li>Total N%</li> </ul>	<ul style="list-style-type: none"> <li>7.9</li> <li>5.7</li> <li>0 cmol.kg<sup>-1</sup></li> <li>146 mS.m<sup>-1</sup></li> <li>18.86%</li> <li>1.1 cmol.kg<sup>-1</sup></li> <li>12.05</li> <li>0.04</li> </ul>	<ul style="list-style-type: none"> <li>pH (KCl)- Alkaline</li> <li>pH (H<sub>2</sub>O)- Acidic</li> <li>Sodic.</li> <li>Low; ameliorated with compost.</li> <li>Low N; C/N ratio unfavourable; ameliorated with fertilizer.</li> </ul>
T8	<ul style="list-style-type: none"> <li>pH (KCl)</li> <li>pH (H<sub>2</sub>O)</li> <li>Al</li> <li>EC</li> <li>ESP</li> <li>CEC</li> <li>Organic C%</li> <li>Total N%</li> </ul>	<ul style="list-style-type: none"> <li>5.5</li> <li>6.0</li> <li>0 cmol.kg<sup>-1</sup></li> <li>11 mS.m<sup>-1</sup></li> <li>2.40%</li> <li>3.6 cmol.kg<sup>-1</sup></li> <li>0.28</li> <li>0.06</li> </ul>	<ul style="list-style-type: none"> <li>Acidic. Calcitic lime added (Ca:Mg ratio of 1:2)</li> <li>Low salinity and sodicity.</li> <li>Relatively moderate CEC; will be further increased with composting.</li> <li>Low; unfavourable C/N ratio; ameliorated with fertilizer and compost.</li> </ul>
T9	<ul style="list-style-type: none"> <li>pH (KCl)</li> <li>pH (H<sub>2</sub>O)</li> <li>Al</li> </ul>	<ul style="list-style-type: none"> <li>3.8</li> <li>2.5</li> <li>21.28 cmol.kg<sup>-1</sup></li> </ul>	<ul style="list-style-type: none"> <li>Extremely acidic; aluminium toxicity; ameliorated with dolomitic lime (Ca:Mg ratio of 6:1)</li> </ul>

	<ul style="list-style-type: none"> <li>• EC ESP</li> <li>• CEC</li> <li>• Organic C% Total N%</li> </ul>	<ul style="list-style-type: none"> <li>• 390 mS.m<sup>-1</sup> 1.49%</li> <li>• 0.8 cmol.kg<sup>-1</sup></li> <li>• 54.34 1.28</li> </ul>	<ul style="list-style-type: none"> <li>• Saline. High SO<sub>4</sub><sup>2-</sup> content: 30 340 mg/L</li> <li>• Very low; ameliorated with compost.</li> <li>• High carbon due to coal (although this is not seen as organic carbon % because it is inactive); low N; C/N ratio unfavourable; ameliorated with fertilizer.</li> </ul>
TC	<ul style="list-style-type: none"> <li>• pH (KCl) pH (H<sub>2</sub>O) Al</li> <li>• EC ESP</li> <li>• CEC</li> <li>• Organic C% Total N%</li> </ul>	<ul style="list-style-type: none"> <li>• 4.1 4.1 0.31 cmol.kg<sup>-1</sup></li> <li>• 13 mS.m<sup>-1</sup> 0.32%</li> <li>• 1.4 cmol.kg<sup>-1</sup></li> <li>• 0.17 0.05</li> </ul>	<ul style="list-style-type: none"> <li>• Acidic; ameliorated with dolomitic lime (Ca:Mg ratio of 1:1)</li> <li>• Low salinity and sodicity.</li> <li>• Low; ameliorated with compost.</li> <li>• Low; unfavourable C/N ratio; ameliorated with lime and compost.</li> </ul>

#### 4.2.1 Discussion of chemical analyses

The chemical analyses of the tailings show several extreme values. The ameliorants applied corrected the chemical imbalances in the tailings and was done prior to the establishment of the plant species.

The tailings are very nutrient poor, except where the mineralogy of the parent rock is rich in a particular element, as is the case with P in T1, and K in T5. Fertilizer formulas suited for each tailings was applied to correct the nutrient imbalances. Further to this, compost added increased organic matter and raised organic carbon levels in the tailings. Dolomitic lime was added to the gypsum (T1), gold (T2), coarse coal (T6), fine coal tailings (T9) and the control soil (TC) and calcitic lime was added to the andalusite tailings (T8). The lime restored the pH of the material to acceptable levels, as well as the Ca:Mg cation imbalances.

Certain tailings show significant  $\Delta\text{pH}$  [ $\text{pH}(\text{KCl}) - \text{pH}(\text{H}_2\text{O})$ ] values (positive or negative). The  $\Delta\text{pH}$  of T4 was measured to be 1.4,  $\Delta\text{pH}$  of T5 was measured to be -2.1 and  $\Delta\text{pH}$  of T7 was measured to be 2.2. According to USDA (1993), the comparison of  $\text{pH}(\text{KCl})$  with  $\text{pH}(\text{H}_2\text{O})$  provides an assessment of the nature of the net charge on the colloidal system. For example, highly weathered oxisols with high amounts of iron oxihydrates have a net positive charge, or anion exchange capacity. If organic matter content is negligible in such soils, the

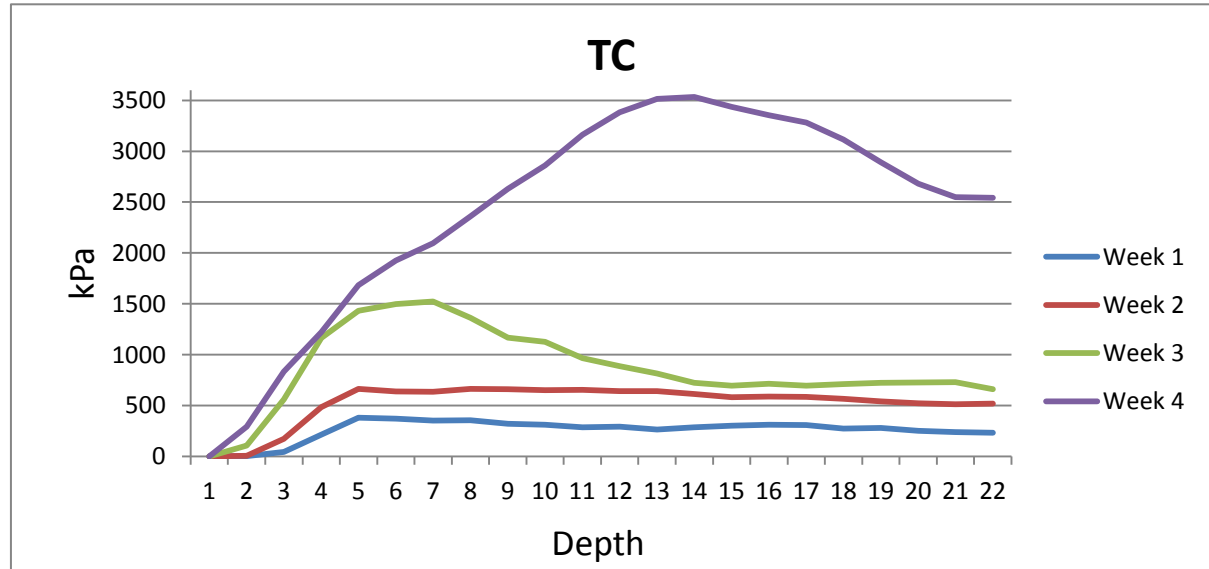
pH(KCl) may be higher than the pH(H<sub>2</sub>O) and the difference results from the Cl<sup>-</sup> ions displacing OH<sup>-</sup>. When the ΔpH is negative, the colloid has a net negative charge and vice versa. ΔpH becomes negligible above 6.5 (USDA, 1993).

The EC of the gold tailings (T3) and coal tailings (T6 and T9) were at high levels. The SO<sub>4</sub><sup>2-</sup> levels in these tailings were found to be extremely high, indicating the presence of secondary sulfate minerals, remnant from the evaporation of acid mine drainage.

### 4.3 Root penetration resistance and gravimetric moisture content over four weeks

**Table 15: Five week penetration resistance of TC (kPa)**

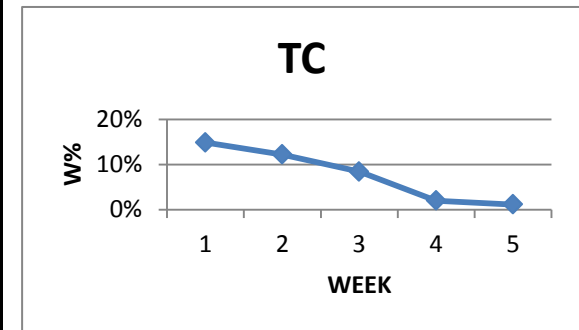
TC				
Depth	Week 1	Week 2	Week 3	Week 4
1	0	0	0	0
2	2.4	7.4	107.2	291.9
3	42.2	172.2	559.8	832
4	212.2	485	1162.4	1222
5	379.8	664.8	1432.2	1682
6	369.8	637.2	1497.2	1925.9
7	352.4	634.8	1522.4	2095.9
8	354.8	664.8	1362.4	2359.2
9	319.8	659.8	1167.2	2631.2
10	309.8	649.8	1125	2859.8
11	284.8	654.8	964.6	3162.2
12	292.2	642.2	887.2	3382.2
13	264.6	642.4	814.6	3514.8
14	287.4	612.2	724.8	3532.2
15	302.2	582.2	694.6	3437.2
16	309.6	589.6	714.6	3354.8
17	307.2	584.8	694.8	3282.2
18	274.8	564.6	712.2	3114.6
19	279.8	539.8	724.8	2892.2
20	249.8	522.4	725	2679.6
21	237.4	512.2	729.6	2549.6
22	232.4	519.8	659.8	2542.4



**Figure 31: Graph indicating increase in resistance in kPa of TC**

**Table 16: Five week gravimetric moisture % of TC**

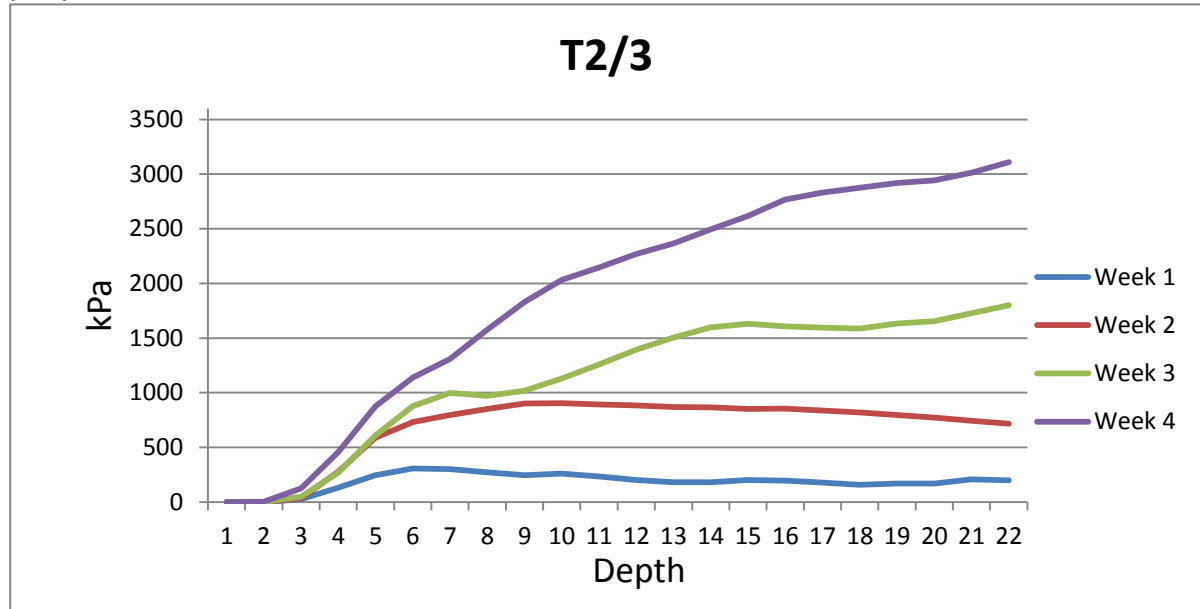
TC				
Week	MT (g)	MS (g)	MW (g)	W%
1	633	539	94	15%
2	418	367	51	12%
3	500	458	42	8%
4	450	441	9	2%
5	433	428	5	1%



**Figure 32: Gravimetric moisture % decline**

**Table 17: Five week penetration resistance of T2/3 (kPa)**

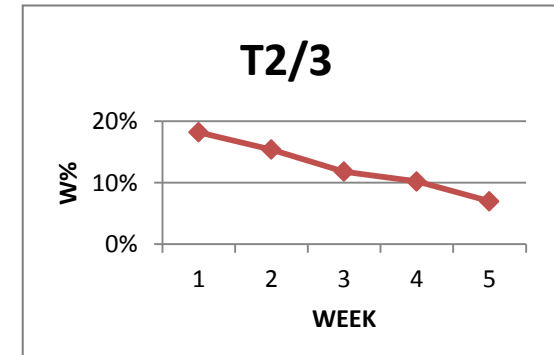
T2/3				
Depth	Week 1	Week 2	Week 3	Week 4
1	0	0	0	0
2	0	0	0	2.4
3	24.8	34.8	49.8	124.8
4	132.2	277.2	267.4	454.8
5	244.6	587.2	607.2	874.6
6	307.4	732.2	877.4	1139.6
7	299.8	794.8	997.4	1307.2
8	272.4	852.2	972.4	1577.4
9	244.8	902.2	1019.6	1829.6
10	259.6	904.8	1129.8	2032.4
11	234.6	892.4	1257.4	2147.4
12	202.2	882.4	1392.4	2270
13	179.6	869.8	1504.8	2367.2
14	182	864.8	1597.4	2495
15	199.8	852.4	1630	2617.4
16	194.8	855	1607.2	2767.4
17	177.2	837.4	1594.8	2832.2
18	157.2	820	1587.4	2874.8
19	169.8	794.8	1632.4	2919.8
20	169.8	772.2	1655	2942.2
21	207.2	742.2	1727.4	3012.2
22	197.2	717.4	1800	3109.8



**Figure 33: Graph indicating increase in resistance in kPa of T2/3**

**Table 18: Five week gravimetric moisture % of T2/3**

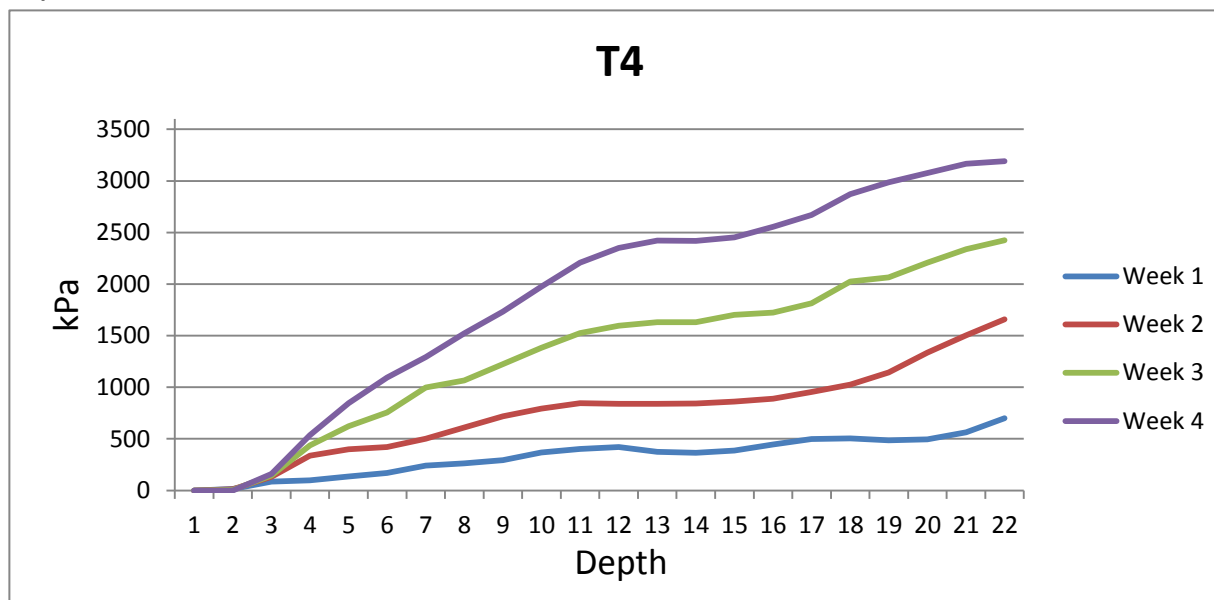
T2/3				
Week	MT (g)	MS (g)	MW (g)	W%
1	512	419	93	18%
2	345	292	53	15%
3	424	374	50	12%
4	304	273	31	10%
5	330	307	23	7%



**Figure 34: Gravimetric moisture % decline**

**Table 19: Five week penetration resistance of T4 (kPa)**

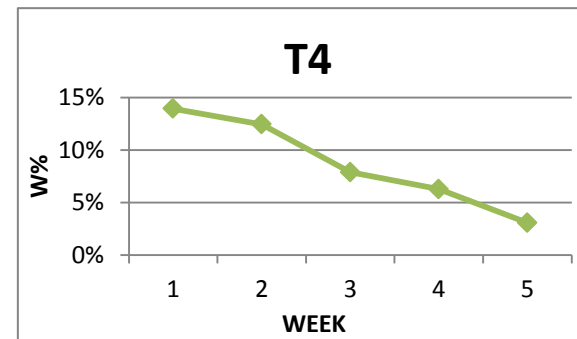
T4				
Depth	Week 1	Week 2	Week 3	Week 4
1	0	0	0	0
2	15	10	5	0
3	85	132.2	146.2	159.6
4	99.8	337.2	436.3	534.8
5	134.8	399.6	622.5	844.8
6	169.8	419.6	757.4	1094.6
7	242.4	502.2	997.4	1292
8	262.4	609.8	1066.4	1522.4
9	292.2	717.4	1225.1	1732.2
10	367.2	792.2	1383.8	1974.6
11	402.2	845	1526.5	2207.2
12	422.2	839.6	1595.1	2349.8
13	374.8	839.8	1631.4	2422.2
14	364.8	842	1630	2417.2
15	387.4	859.8	1701.5	2453.4
16	444.6	889.8	1722.7	2554.8
17	497.4	954.6	1812.6	2669.8
18	504.8	1024.8	2025.4	2872.4
19	484.8	1144.8	2065.8	2985
20	494.8	1337.2	2208.2	3077.4
21	564.6	1504.8	2336.9	3167.2
22	699.6	1657.2	2425.6	3192.2



**Figure 35: Graph indicating increase in resistance in kPa of T4**

**Table 20: Five week gravimetric moisture % of T4**

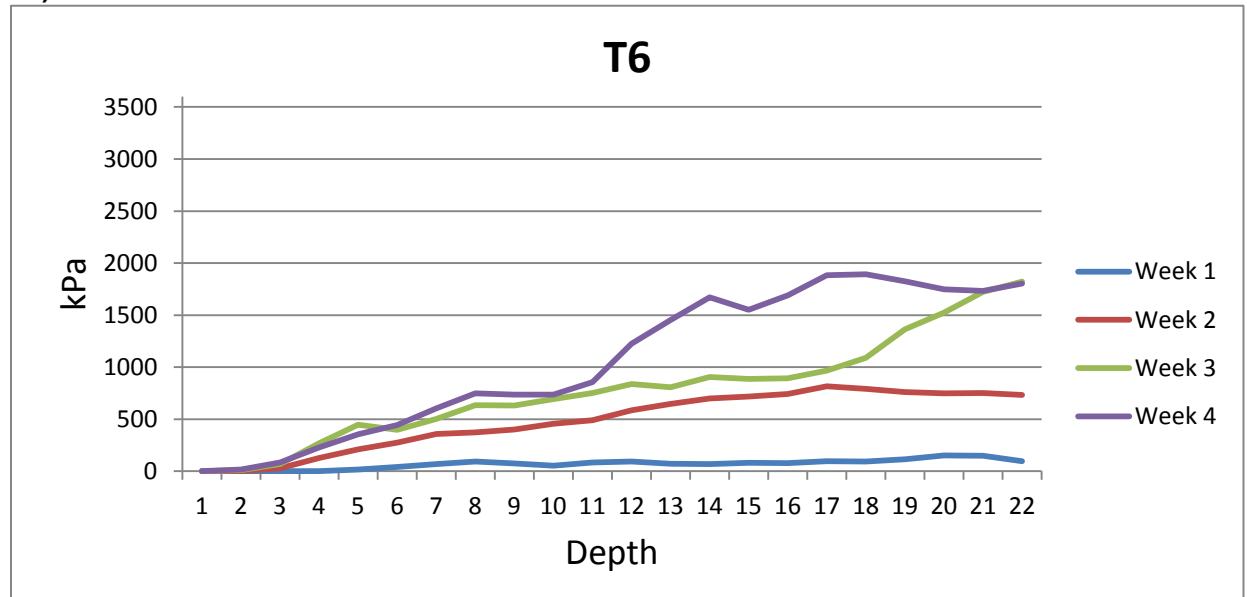
T4				
Week	MT (g)	MS (g)	MW (g)	W%
1	625	538	87	14%
2	394	345	49	12%
3	559	515	44	8%
4	447	419	28	6%
5	458	444	14	3%



**Figure 36: Gravimetric moisture % decline**

**Table 21: Five week penetration resistance of T6 (kPa)**

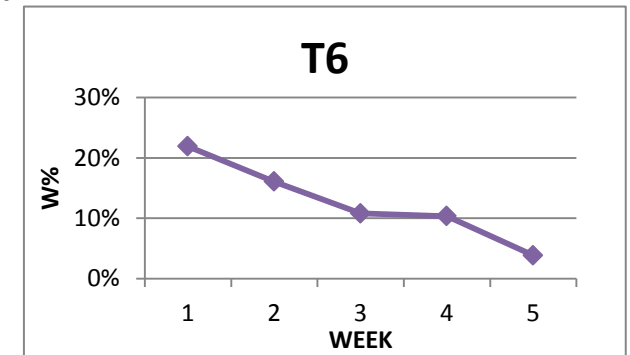
T6				
Depth	Week 1	Week 2	Week 3	Week 4
1	0	0	0	0
2	0	2.4	10	17.4
3	0	29.8	70	85
4	0	127.2	270	229.8
5	17.4	209.6	447.4	354.8
6	39.8	274.8	397.4	442.4
7	69.8	357	502.2	604.6
8	92.4	372.2	634.8	749.8
9	75	399.8	632.2	734.8
10	52.4	457.2	692.4	737.2
11	84.8	489.8	752.4	857.2
12	92.4	584.6	837	1224.8
13	72.4	647.2	807.2	1452.4
14	69.8	699.8	904.6	1669.8
15	82.2	717.2	887.2	1552.4
16	77.4	742.2	892.4	1690
17	97.4	817.2	967.2	1882.2
18	94.8	792.4	1089.8	1892.4
19	114.8	759.8	1362.2	1824.8
20	152.2	749.8	1524.8	1747.4
21	149.8	752.4	1724.8	1732.2
22	95	732.4	1822.2	1802.2



**Figure 37: Graph indicating increase in resistance in kPa of T6**

**Table 22: Five week gravimetric moisture % of T6**

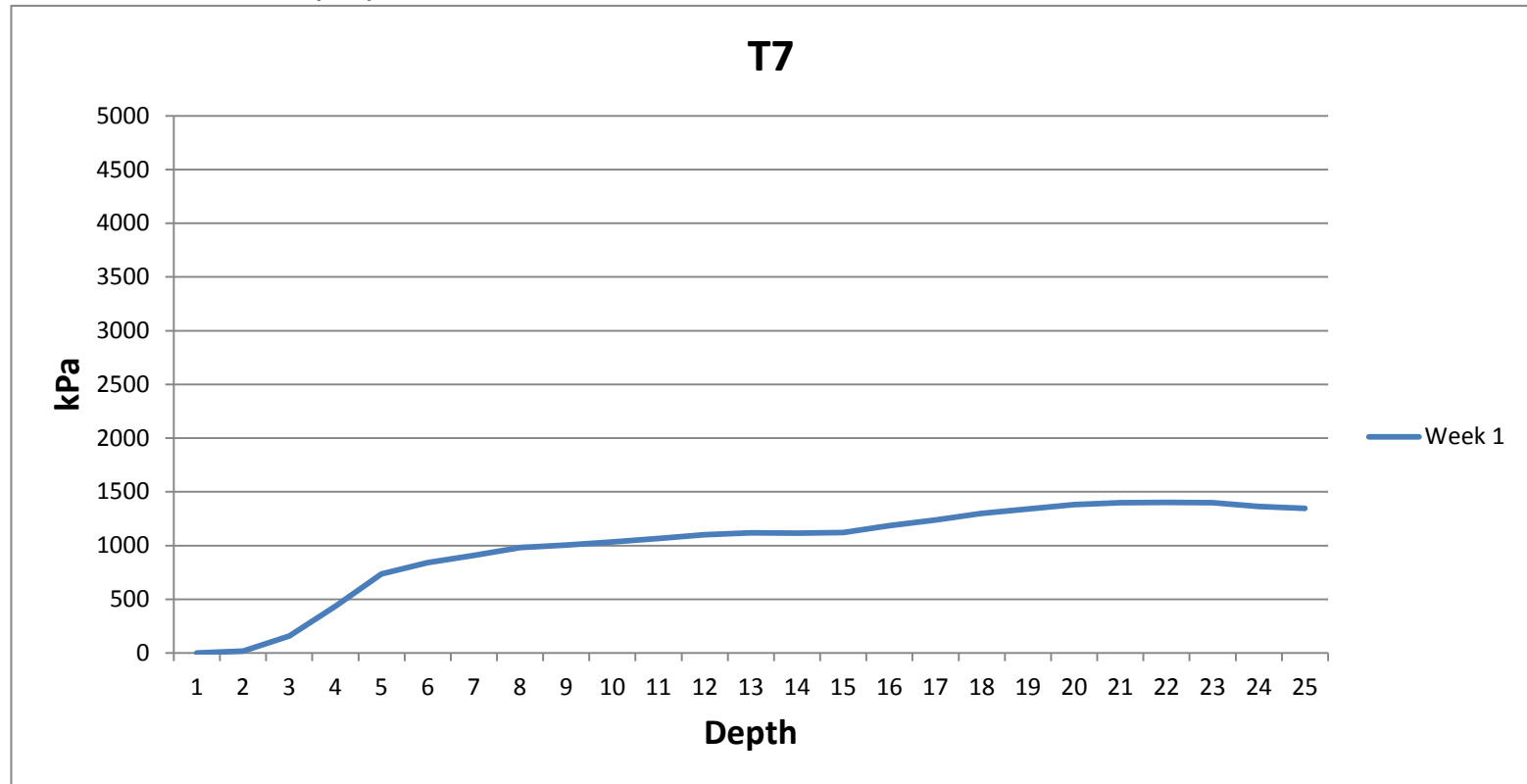
T6				
Week	MT (g)	MS (g)	MW (g)	W%
1	370	289	81	22%
2	274	230	44	16%
3	324	289	35	11%
4	280	251	29	10%
5	312	300	12	4%



**Figure 38: Gravimetric moisture % decline**

**Table 23: Five week penetration resistance of T7 (kPa)**

T7	
Depth	Week 1
1	0
2	17.4
3	157.2
4	435
5	734.8
6	839.8
7	907
8	982.4
9	1004.6
10	1034.6
11	1064.6
12	1099.8
13	1117.4
14	1114.8
15	1122.2
16	1184.8
17	1237.2
18	1299.8
19	1339.8
20	1379.8
21	1397.2
22	1402.2
23	1397.4
24	1364.8
25	1344.8



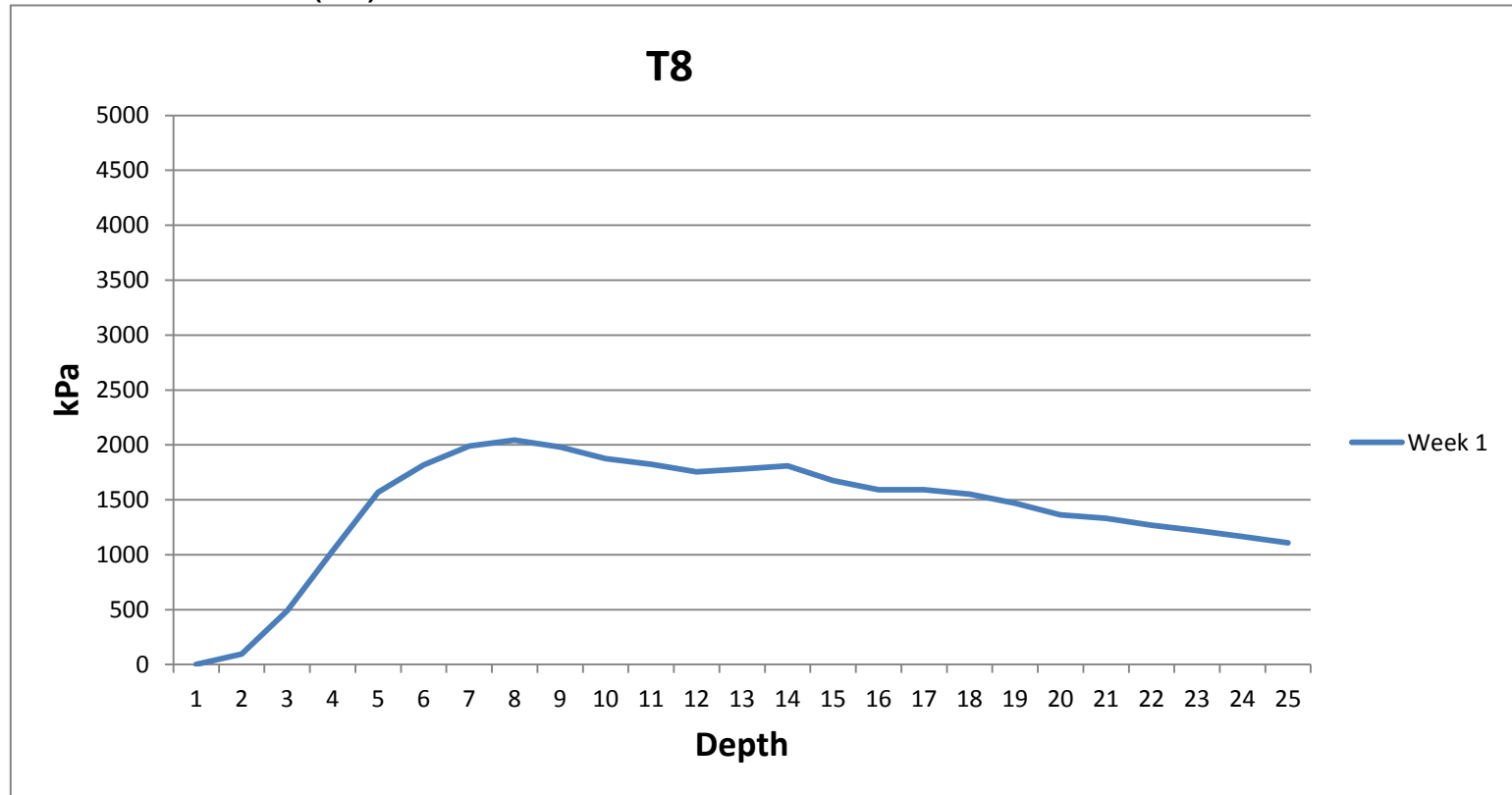
**Figure 39: Graph indicating penetration resistance of T7 at 7% gravimetric moisture**

**Table 24: Gravimetric moisture content**

T7				
Week	MT (g)	MS (g)	MW (g)	W%
1	524	469	55	10%

**Table 25: Five week penetration resistance of T8 (kPa)**

T8	
Depth	Week 1
1	0
2	94.8
3	489.6
4	1034.6
5	1569.8
6	1817.2
7	1989.8
8	2044.8
9	1979.8
10	1874.6
11	1822.2
12	1754.8
13	1780
14	1809.8
15	1674.6
16	1592.2
17	1592.4
18	1552.2
19	1469.8
20	1362.4
21	1332.4
22	1269.8
23	1219.6
24	1164.8
25	1107.4



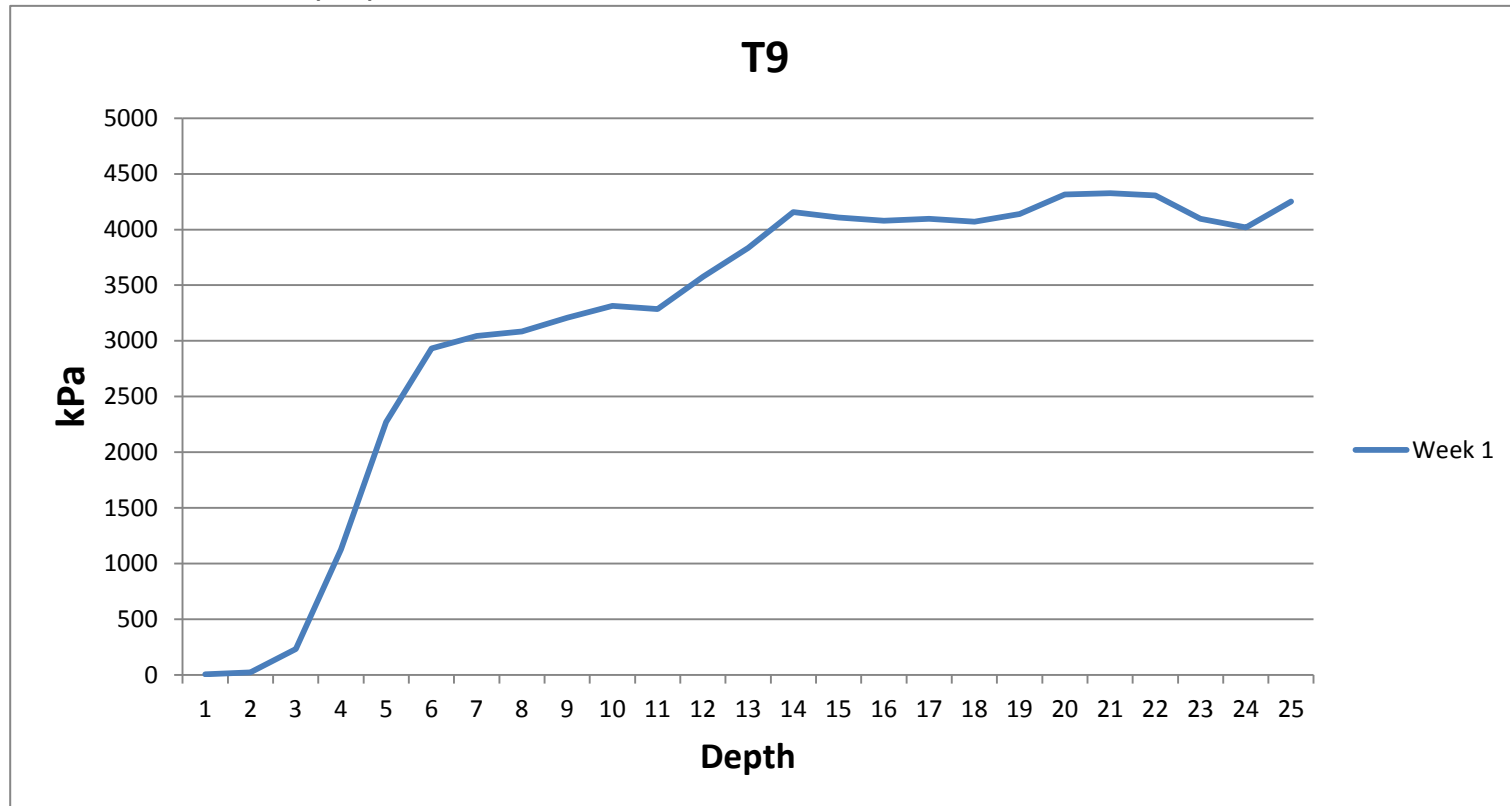
**Figure 40: Graph indicating penetration resistance of T8 at 11% gravimetric moisture**

**Table 26: Gravimetric moisture content**

T8				
Week	MT (g)	MS (g)	MW (g)	W%
1	636	566	70	11%

**Table 27: Five week penetration resistance of T9 (kPa)**

T9	
Depth	Week 1
1	4.8
2	22.4
3	232.2
4	1127.2
5	2272
6	2932.4
7	3044.8
8	3084.6
9	3207.4
10	3314.8
11	3287.2
12	3577.2
13	3834.6
14	4157.2
15	4107.4
16	4079.8
17	4097.4
18	4070
19	4139.8
20	4315
21	4325
22	4307.4
23	4097.4
24	4020
25	4252.4



**Figure 41: Graph indicating penetration resistance of T9 at 18% gravimetric moisture**

**Table 28: Gravimetric moisture content**

T9				
Week	MT (g)	MS (g)	MW (g)	W%
1	611	520	91	15%

#### 4.3.1 Discussion of Root penetration resistance and gravimetric moisture content

According to Taylor *et al.* (1966), as well as Benjamin *et al.* (2003 [both cited by Reichert *et al.*, 2004:1) the maximum value of 2000 kPa for root penetration resistance is widely accepted as critical for root growth. (Reichert *et al.*, 2004:1)

According to Ayers & Perumpral (1982), as well as Gliński & Lipiec (1990 [both cited by Quang *et al.*, 2012:84]), the penetration resistance of a soil depends on soil type, bulk density and soil water content. Soil water content affects cohesion, angle of internal friction, compressibility and adhesion of particles. (Quang *et al.*, 2012:84)

Because of the effect of moisture content on penetration resistance (PR), the gravimetric moisture contents (W) of the different tailings were determined every day when readings were taken. Bulk densities of the different tailings were determined as well, as seen in Table 13.

The penetration resistance (in kPa) of the different tailings and the gravimetric moisture content at the time readings were taken, are illustrated by Tables 15 to 28, as well as Figures 31 to 41.

As illustrated by Figure 31, the control soil (TC) experienced an increase in penetration resistance over four weeks. In weeks one and two, penetration resistance increased from 0 – 5 cm and then remained roughly constant down to 22 cm. A compacted layer seems to have formed in week three (W = 8%) at 4 – 8 cm, with PR increasing rapidly down to 4 cm and decreasing gradually from 8 cm downwards. In week three, the peak was at 1500 kPa. In week four (W = 2%) a sharp increase in PR can be seen with the threshold of 2000 kPa already reached at 4 cm. This soil is very prone to compaction and/or hardsetting under dry conditions. Coupled with low water retention, this could have been a major contribution to the overall weak growth of plants in the control soil.

As illustrated by Figure 33, the penetration resistance of the gold tailings (T2 and T3) increased at a steady rate over the four weeks. For the first two weeks, with moisture contents > 15 as seen in Table 18, the PR increased down to a depth of 6 cm, and then remained roughly constant down to 22 cm. In week three (W = 12%), the PR increased gradually with depth (0 – 22 cm), peaking at 1800 kPa. The graph does however indicate that PR remained constant at two short intervals (6 – 8 cm; 14 – 17 cm), therefore the tailings had not compacted entirely. In week four (W = 10%), the PR showed a sharp increase with depth, with the threshold value of 2000 kPa being reached at ± 9 cm. The conclusion drawn is that the PR of these tailings to root penetration reaches a critical level at ± 10 - 11% gravimetric moisture content.

The penetration resistance of the platinum tailings (T4), increased at a steady rate over the period of two weeks (Figure 35). For each week, the penetration resistance increased steadily with depth and there is no evidence of crusting. In week three, at a depth of ± 17 – 18 cm and gravimetric moisture content of 8%, the critical PR value for plant roots (2000 kPa) is reached. In week four, this critical value is reached at 9 – 10 cm (W = 6%). The high PR values of T4 can be attributed to the high bulk density, as well as low water retention.

The kimberlite tailings (T5) are not included because the coarse texture of the tailings causes inaccurate readings. Because the material is crushed kimberlite rock it could also damage the shaft of the P5 penetrometer.

As seen in Figure 37, which is of the coarse coal tailings (T6), it is difficult to get accurate data for coarse mediums. Although a steady weekly increase in penetration resistance can be seen, the lines plotted for each week differ and show up- and downward spikes. This is due to porosity, different grain sizes and rocks. If the tip of the penetrometer should touch a rock or move through a porous section, spikes in the readings may occur.

For T7, T8 and T9 a different method was used. The tailings were left to dry for several weeks, so the maximum penetration resistance could be measured.

As seen in Figure 39, the fluorspar tailings (T7), did not reach significant PR levels. The reason for this is that the moisture content was not yet very low ( $W = 10\%$ ). With further dewatering the tailings should compact more, resulting in a higher PR. The high bulk density ( $1.51 \text{ g.cm}^3$ ) also suggests a possibility of high PR.

Figure 40 illustrates that T8 reached 2000 kPa at 6 cm, whereafter PR decreased gradually to 1000 kPa at 25 cm. As was the case with T7, the tailings still had a high water content ( $W = 11\%$ ). Field observations proved this tailings type to be very prone to hardsetting, therefore a high PR is to be expected. If the moisture content of the T8 reaches significantly low levels, high PR is to be expected.

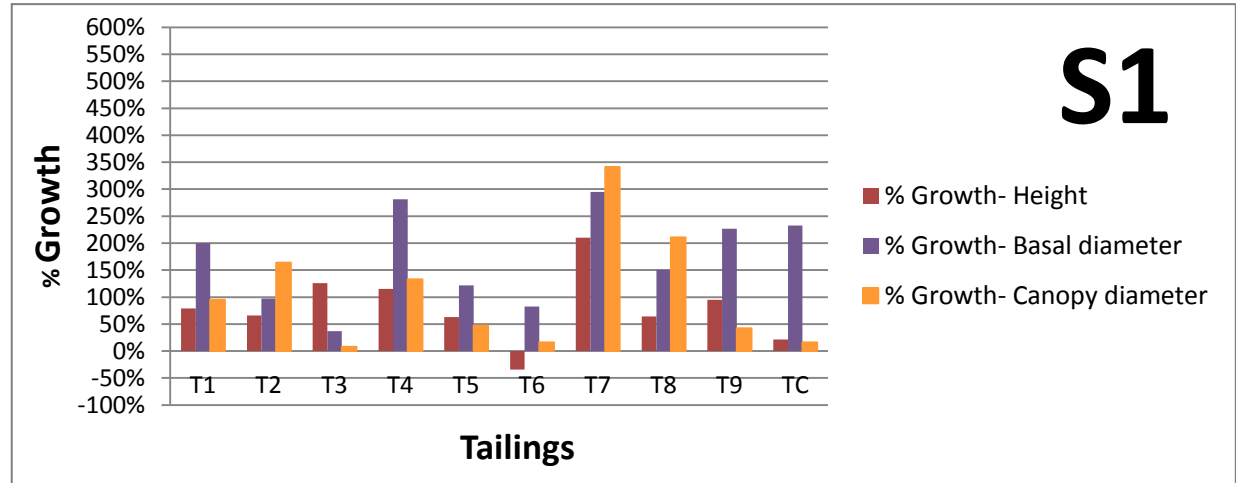
As seen from Figure 41, the fine coal tailings (T9), is extremely prone to hardsetting. Penetration resistance increased dramatically from 0 – 4 cm, where 2000 kPa was reached and the PR continued to increase. From  $\pm 12$  cm downwards the PR remains between 4000 and 4500 kPa. The conclusion drawn is that T9 is prone to extreme hardsetting under dry conditions, therefore severely obstructing root development.

#### **4.4 Plant growth percentage tables and graphs**

Tables 29 to 50 contain the growth percentages used to calculate the final index values, whilst Figure 42 to 63 was used as another tool to visually illustrate the data. On the x-axis are the various tailings and on the y-axis the percentage growth. Three different bars are shown – height, canopy diameter and basal diameter. Each graph is for a different species. The particular significance these graphs have is that they show the control, TC, alongside the other tailings, therefore a comparison can be made. By comparing to TC, the results that can truly be attributed to the specific tailings are more apparent. Another set of similar tables and graphs (Tables 58 to 61 and Figures 65 to 74), this time with the species on the x-axis, are included in Appendix 1. These are not as useful in illustrating the data as the aforementioned graphs.

**Table 29: Growth percentages of S1**

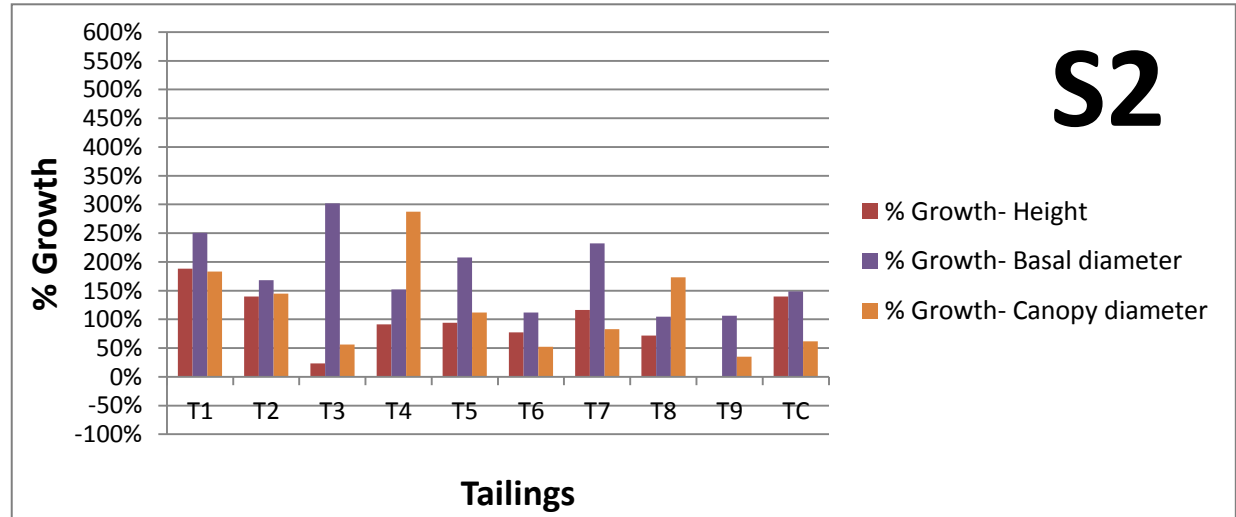
<b>S1</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	79%	200%	95%
T2	66%	98%	164%
T3	126%	37%	8%
T4	115%	281%	133%
T5	63%	121%	47%
T6	-34%	83%	16%
T7	210%	295%	341%
T8	64%	151%	211%
T9	95%	227%	42%
TC	21%	233%	16%



**Figure 42: Graph of S1 with all tailings on the x-axis, indicating growth percentage of S1 on the y-axis**

**Table 30: Growth percentages of S2**

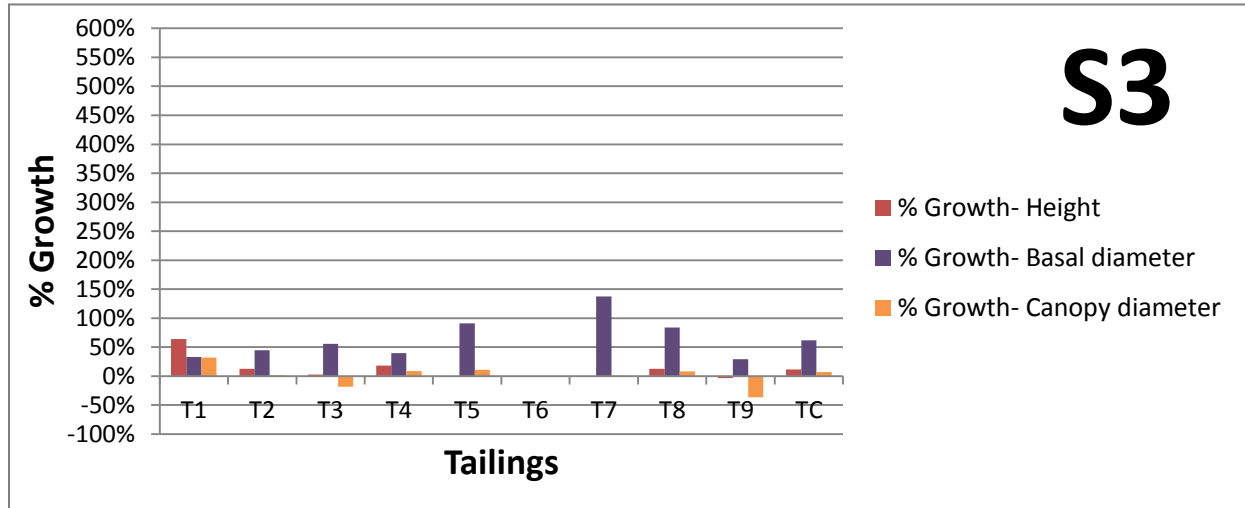
<b>S2</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	188%	251%	183%
T2	140%	168%	145%
T3	23%	302%	56%
T4	91%	152%	287%
T5	94%	208%	112%
T6	78%	112%	53%
T7	116%	232%	83%
T8	72%	105%	173%
T9	0%	106%	35%
TC	140%	149%	62%



**Figure 43: Graph of S2 with all tailings on the x-axis, indicating growth percentage of S2 on the y-axis**

**Table 31: Growth percentages of S3**

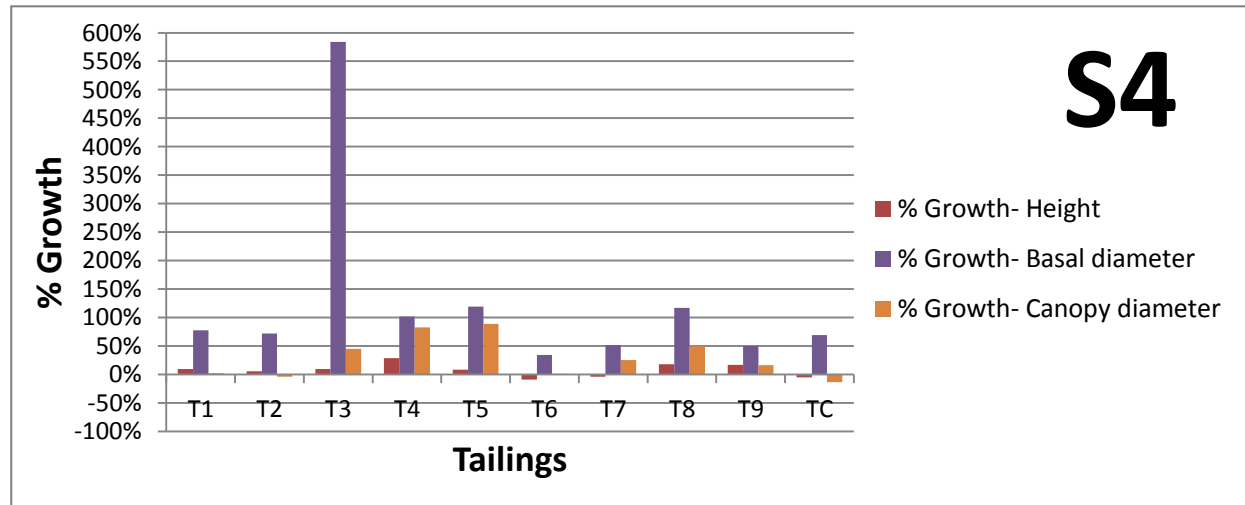
<b>S3</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	64%	33%	32%
T2	12%	45%	2%
T3	3%	56%	-18%
T4	18%	40%	9%
T5	0%	91%	11%
T6	0%	0%	0%
T7	-1%	138%	1%
T8	13%	84%	8%
T9	-3%	29%	-37%
TC	11%	62%	7%



**Figure 44: Graph of S3 with all tailings on the x-axis, indicating growth percentages of S3 on the y-axis**

**Table 32: Growth percentages of S4**

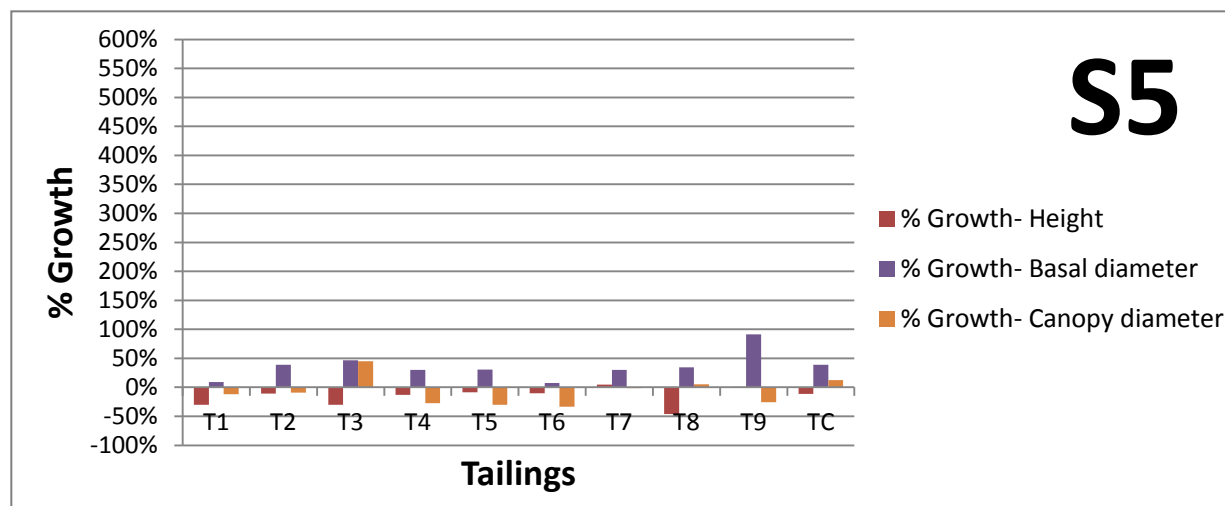
<b>S4</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	10%	78%	2%
T2	6%	72%	-4%
T3	10%	584%	45%
T4	29%	102%	83%
T5	9%	119%	89%
T6	-9%	35%	1%
T7	-4%	52%	25%
T8	18%	117%	49%
T9	17%	50%	16%
TC	-5%	69%	-13%



**Figure 45: Graph of S4 with all tailings on the x-axis, indicating growth percentages of S4 on the y-axis**

**Table 33: Growth percentages of S5**

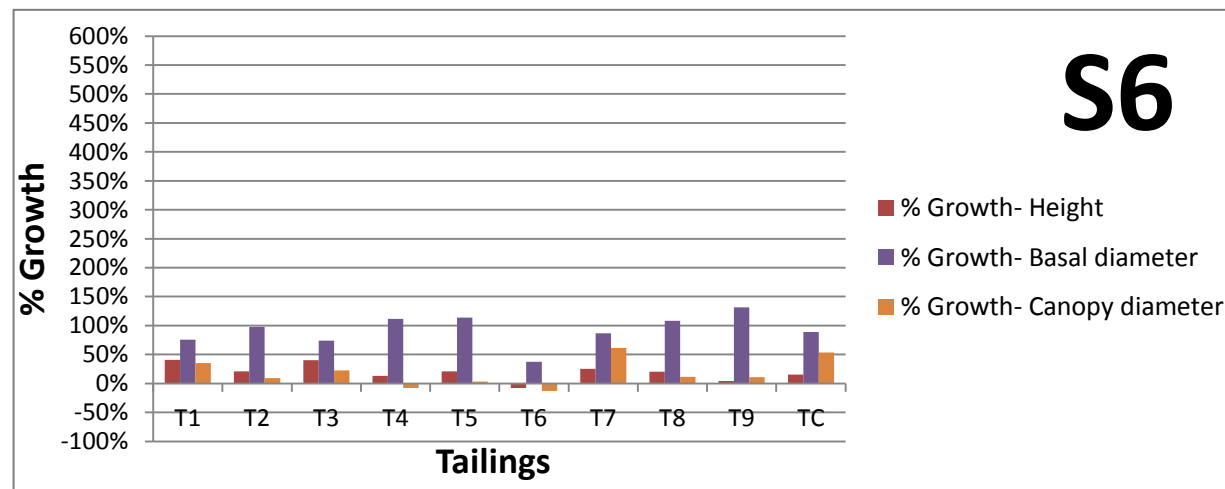
<b>S5</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	-30%	9%	-12%
T2	-11%	39%	-9%
T3	-30%	47%	45%
T4	-13%	30%	-27%
T5	-9%	31%	-30%
T6	-11%	8%	-34%
T7	5%	30%	-1%
T8	-46%	34%	5%
T9	0%	91%	-26%
TC	-11%	39%	12%



**Figure 46: Graph of S5 with all tailings on the x-axis, indicating growth percentages of S5 on the y-axis**

**Table 34: Growth percentages of S6**

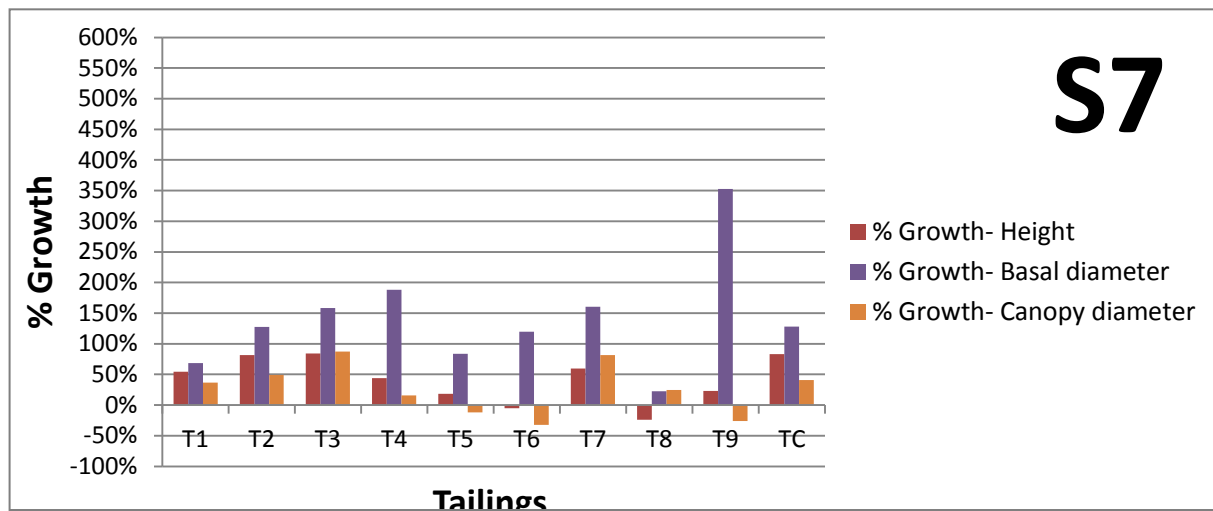
<b>S6</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	41%	76%	35%
T2	21%	98%	9%
T3	40%	74%	23%
T4	13%	111%	-8%
T5	21%	114%	3%
T6	-8%	38%	-13%
T7	25%	87%	61%
T8	21%	108%	12%
T9	4%	132%	11%
TC	16%	89%	53%



**Figure 47: Graph of S6 with all tailings on the x-axis, indicating growth percentages of S6 on the y-axis**

**Table 35: Growth percentages of S7**

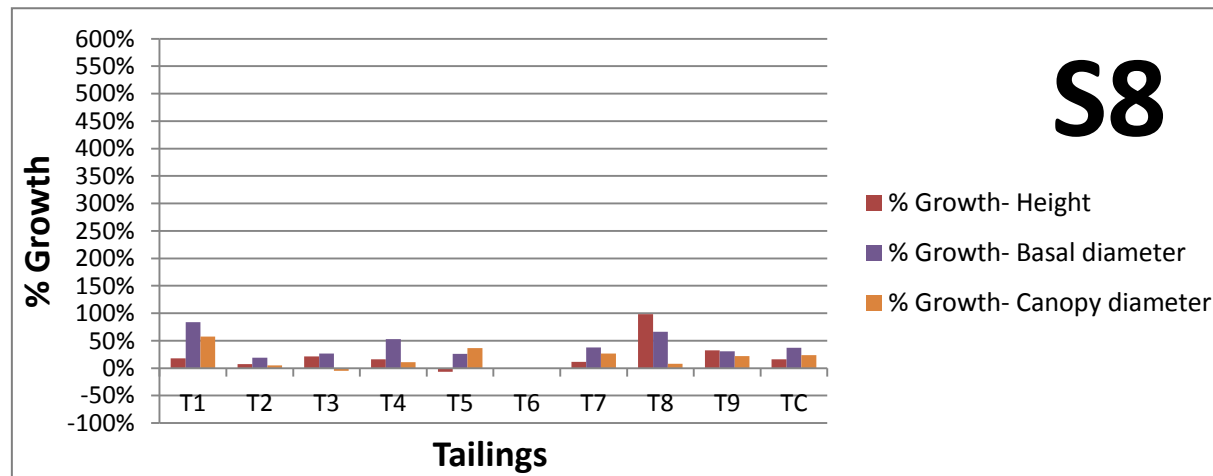
<b>S7</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	55%	69%	36%
T2	82%	127%	49%
T3	84%	158%	87%
T4	44%	188%	16%
T5	18%	84%	-12%
T6	-5%	120%	-32%
T7	59%	161%	82%
T8	-24%	23%	24%
T9	23%	353%	-26%
TC	83%	128%	41%



**Figure 48: Graph of S7 with all tailings on the x-axis, indicating growth percentages of S7 on the y-axis**

**Table 36: Growth percentages of S8**

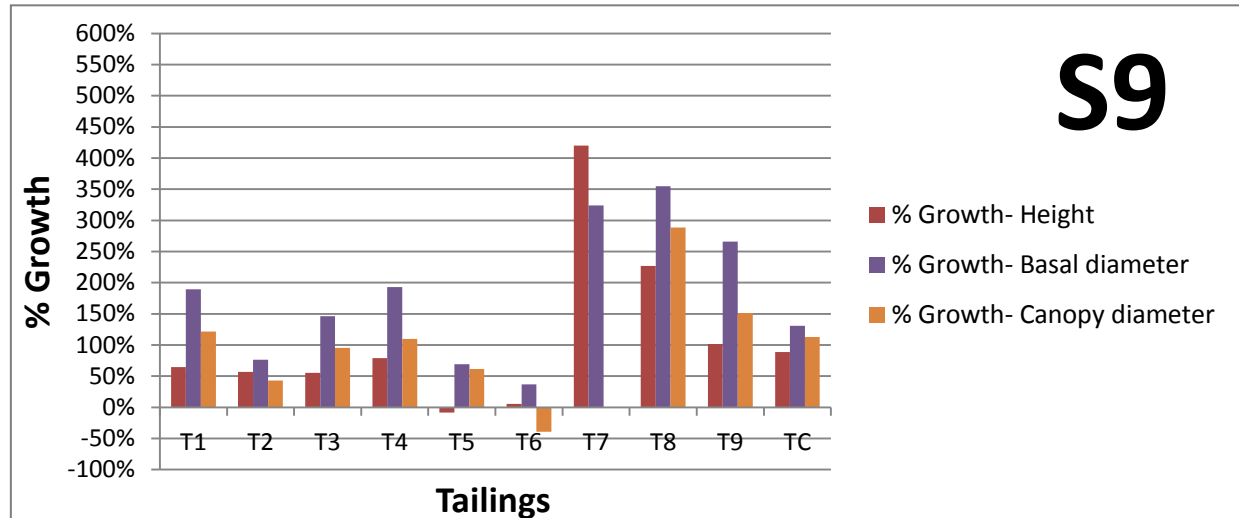
<b>S8</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	18%	84%	58%
T2	7%	19%	5%
T3	21%	27%	-5%
T4	16%	53%	11%
T5	-7%	26%	37%
T6	0%	0%	0%
T7	11%	38%	27%
T8	98%	66%	8%
T9	33%	31%	22%
TC	16%	37%	24%



**Figure 49: Graph of S8 with all tailings on the x-axis, indicating growth percentages of S8 on the y-axis**

**Table 37: Growth percentages of S9**

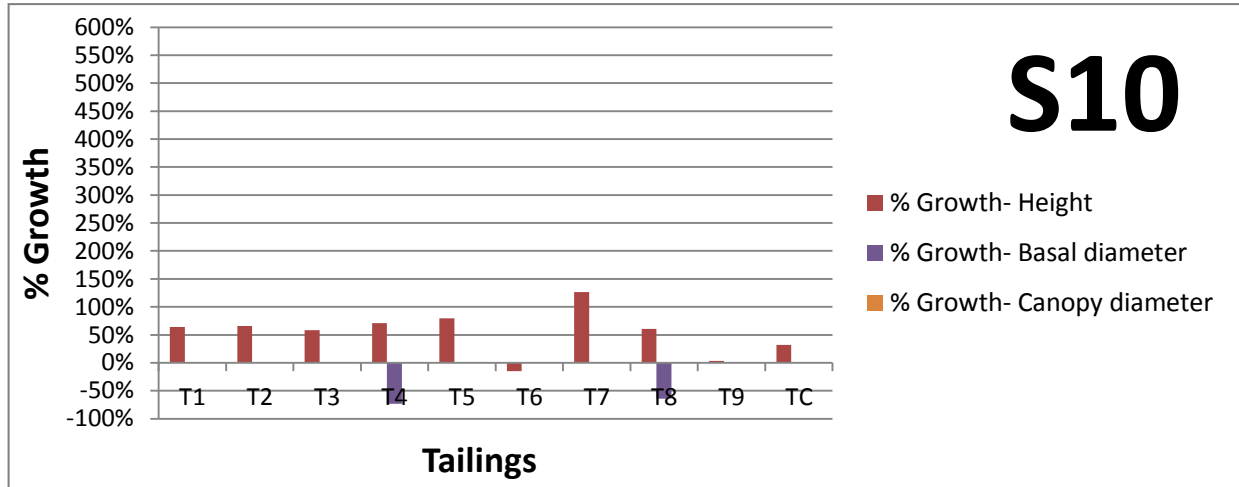
S9	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	65%	189%	122%
T2	57%	76%	43%
T3	55%	146%	95%
T4	79%	193%	110%
T5	-8%	69%	62%
T6	6%	37%	-39%
T7	420%	324%	0%
T8	227%	355%	289%
T9	102%	266%	151%
TC	89%	131%	113%



**Figure 50: Graph of S9 with all tailings on the x-axis, indicating growth percentages of S9 on the y-axis**

**Table 38: Growth percentages of S10**

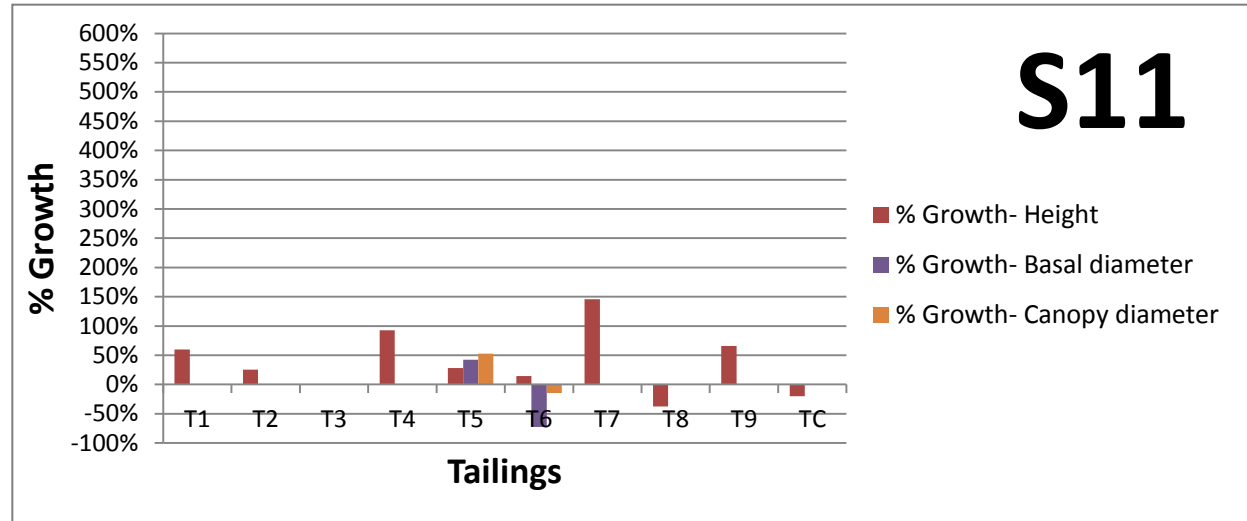
S10	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	64%	0%	0%
T2	66%	0%	0%
T3	58%	0%	0%
T4	71%	-74%	0%
T5	79%	0%	0%
T6	-15%	0%	0%
T7	126%	0%	0%
T8	61%	-64%	0%
T9	3%	0%	0%
TC	32%	0%	0%



**Figure 51: Graph of S10 with tailings on the x-axis, indicating growth percentages of S10 on the y-axis**

**Table 39: Growth percentages of S11**

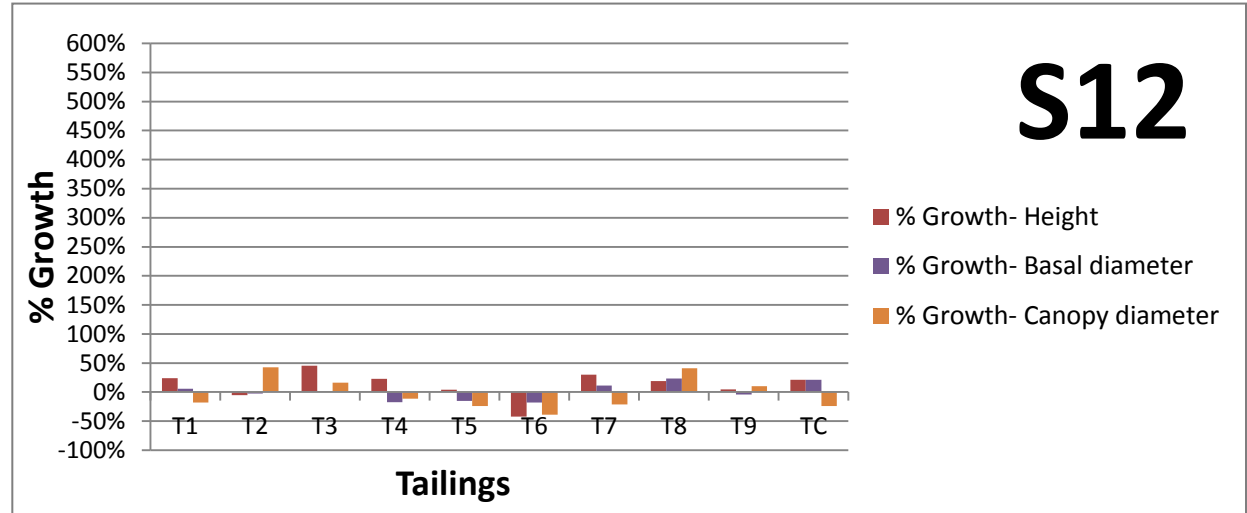
S11	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	60%	0%	0%
T2	26%	0%	0%
T3	0%	0%	0%
T4	93%	0%	0%
T5	28%	42%	53%
T6	14%	-73%	-15%
T7	146%	0%	0%
T8	-38%	0%	0%
T9	66%	0%	0%
TC	-20%	0%	0%



**Figure 52: Graph of S11 with tailings on the x-axis, indicating growth percentages of S11 on the y-axis**

**Table 40: Growth percentages of S12**

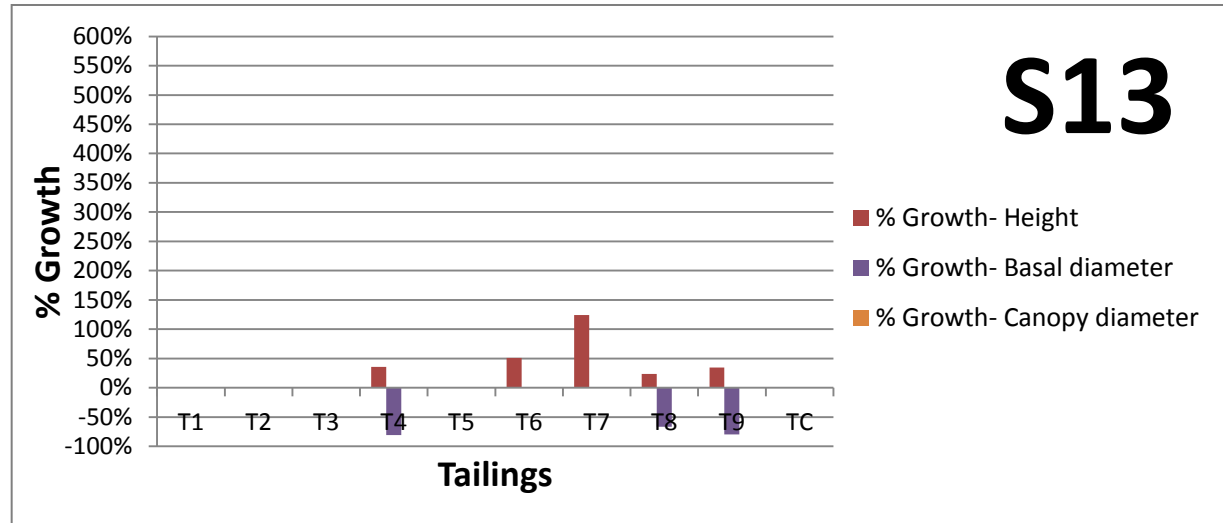
S12	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	24%	5%	-18%
T2	-5%	-3%	43%
T3	46%	1%	16%
T4	23%	-17%	-12%
T5	4%	-15%	-24%
T6	-42%	-18%	-39%
T7	30%	11%	-21%
T8	19%	23%	41%
T9	4%	-4%	10%
TC	21%	21%	-24%



**Figure 53: Graph of S12 with tailings on the x-axis, indicating growth percentages of S12 on the y-axis**

**Table 41: Growth percentages of S13**

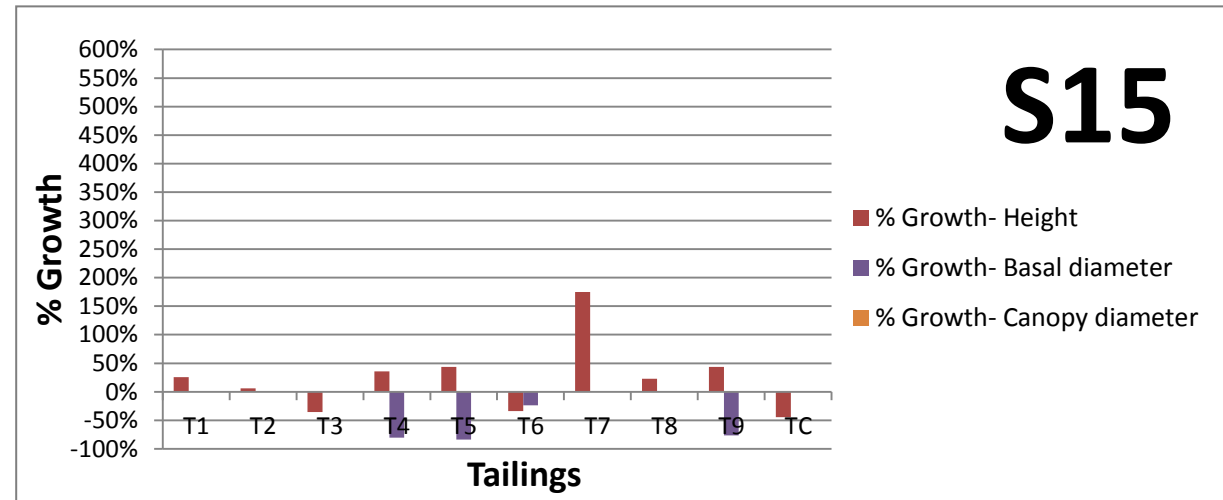
<b>S13</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	0%	0%	0%
T2	0%	0%	0%
T3	0%	0%	0%
T4	36%	-81%	0%
T5	0%	0%	0%
T6	51%	0%	0%
T7	124%	0%	0%
T8	24%	-67%	0%
T9	35%	-79%	0%
TC	0%	0%	0%



**Figure 54: Graph of S13 with tailings on the x-axis, indicating growth percentage of S13 on the y-axis**

**Table 42: Growth percentages of S15**

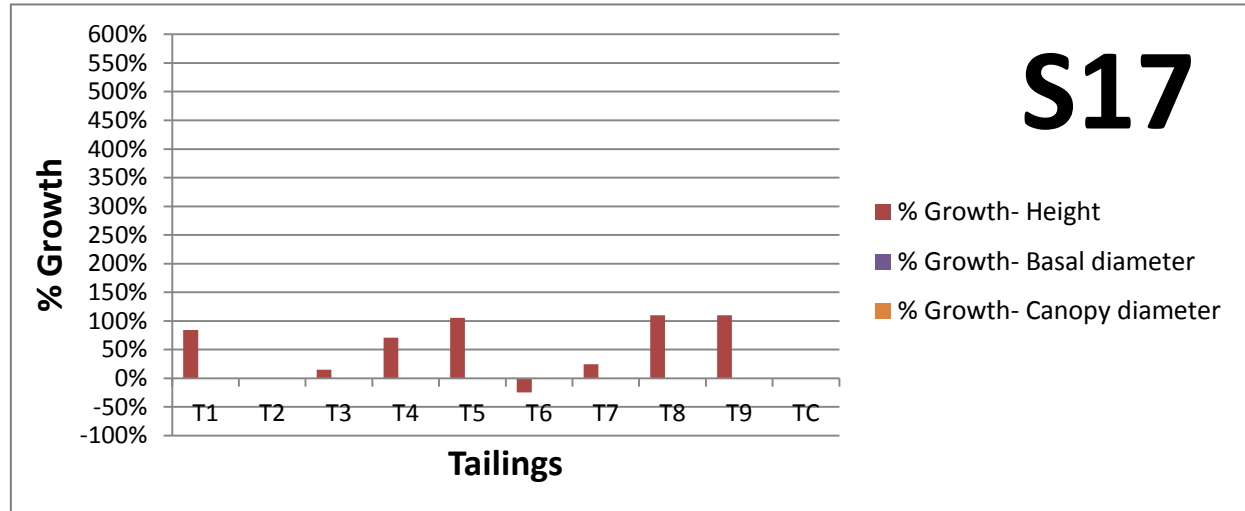
<b>S15</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	26%	0%	0%
T2	6%	0%	0%
T3	-36%	0%	0%
T4	36%	-81%	0%
T5	44%	-84%	0%
T6	-34%	-24%	0%
T7	175%	0%	0%
T8	23%	0%	0%
T9	43%	-77%	0%
TC	-44%	0%	0%



**Figure 55: Graph of S15 with tailings on the x-axis, indicating growth percentage of S15 on the y-axis**

**Table 43: Growth percentages of S17**

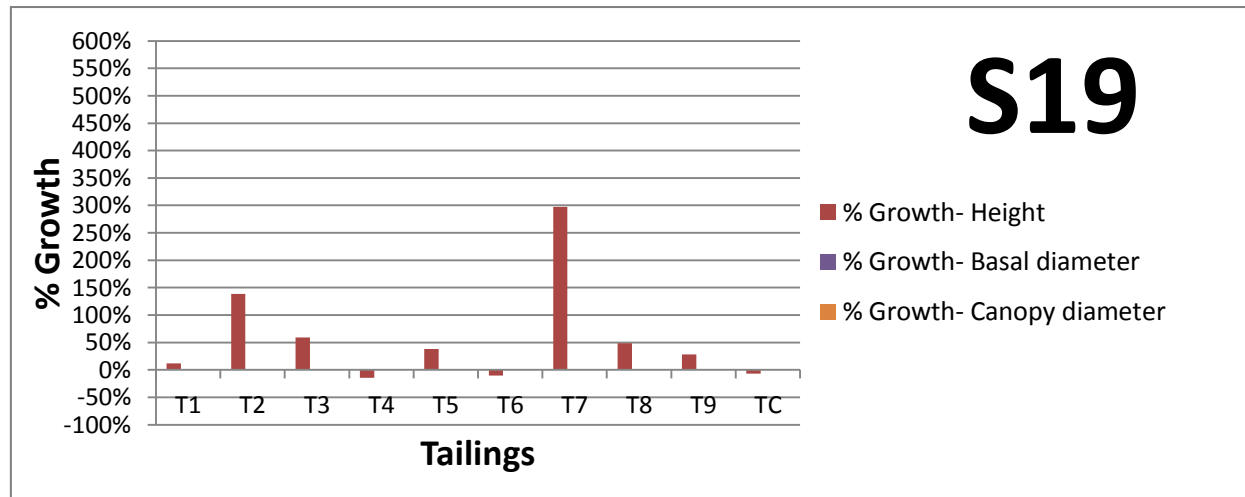
<b>S17</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	84%	0%	0%
T2	0%	0%	0%
T3	15%	0%	0%
T4	71%	0%	0%
T5	105%	0%	0%
T6	-25%		
T7	25%	0%	0%
T8	110%	0%	0%
T9	110%	0%	0%
TC	0%	0%	0%



**Figure 56: Graph of S17 with tailings on the x-axis, indicating growth percentage of S17 on the y-axis**

**Table 44: Growth percentages of S19**

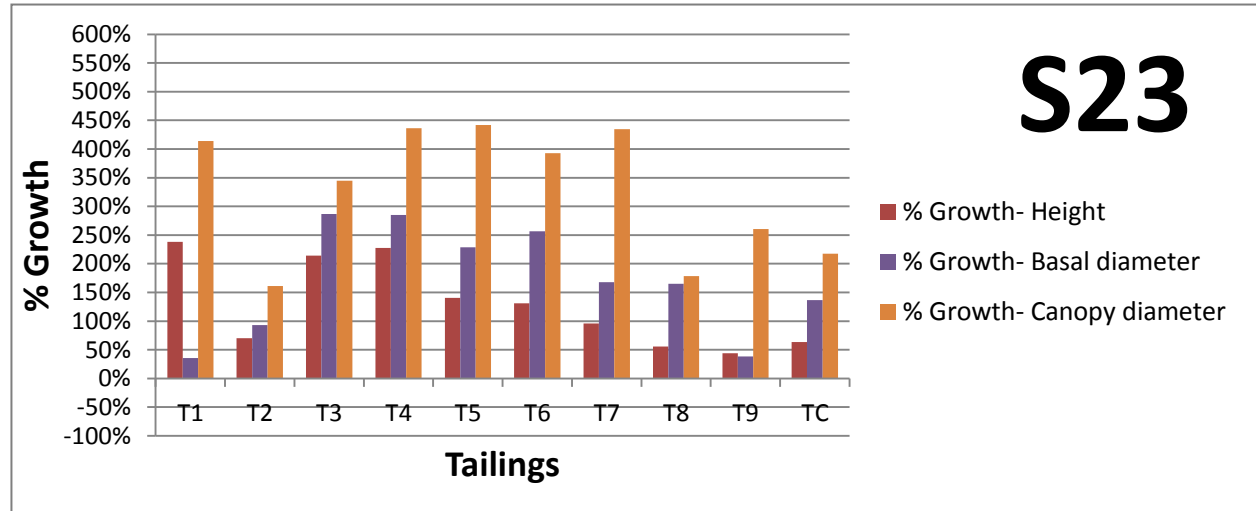
<b>S19</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	12%	0%	0%
T2	138%	0%	0%
T3	59%	0%	0%
T4	-14%	0%	0%
T5	38%	0%	0%
T6	-10%	0%	0%
T7	297%	0%	0%
T8	48%	0%	0%
T9	28%	0%	0%
TC	-7%	0%	0%



**Figure 57: Graph of S19 with tailings on the x-axis, indicating growth percentage of S19 on the y-axis**

**Table 45: Growth percentages of S23**

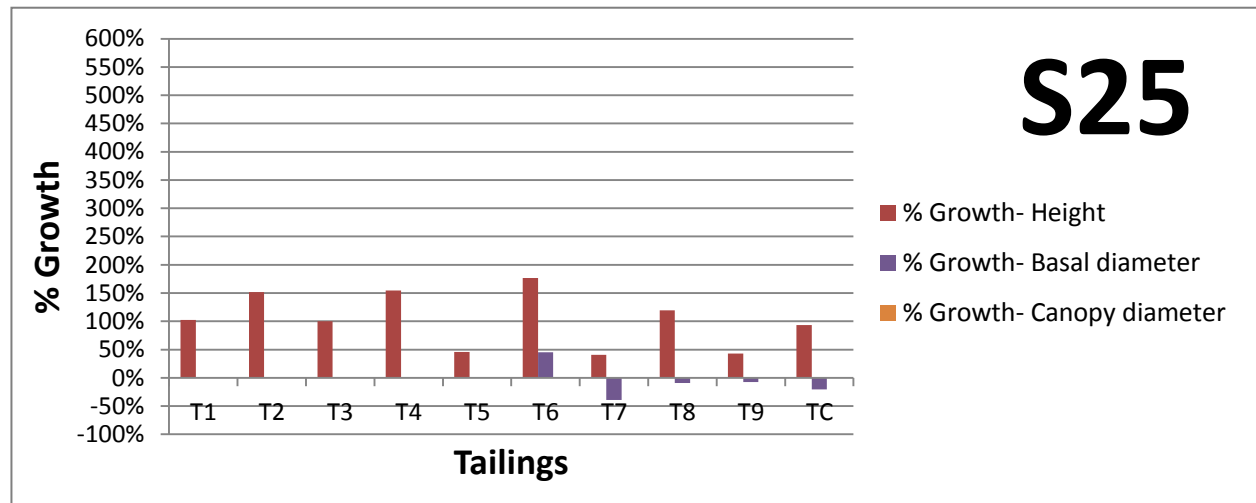
<b>S23</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	238%	36%	414%
T2	70%	93%	161%
T3	214%	287%	345%
T4	228%	285%	436%
T5	141%	229%	442%
T6	131%	257%	393%
T7	96%	168%	434%
T8	55%	165%	179%
T9	44%	38%	261%
TC	63%	137%	218%



**Figure 58: Graph of S23 with tailings on the x-axis, indicating growth percentage of S23 on the y-axis**

**Table 46: Growth percentages of S25**

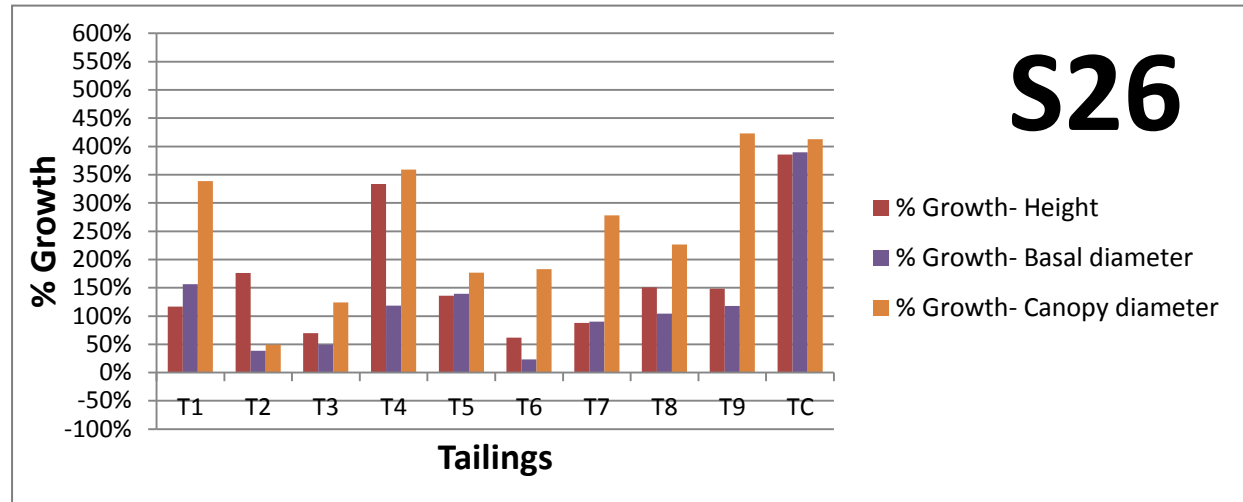
<b>S25</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	102%	0%	0%
T2	152%	0%	0%
T3	100%	0%	0%
T4	154%	0%	0%
T5	46%	1%	0%
T6	176%	45%	0%
T7	41%	-39%	0%
T8	120%	-9%	0%
T9	43%	-7%	0%
TC	93%	-21%	0%



**Figure 59: Graph of S25 with tailings on the x-axis, indicating growth percentage of S25 on the y-axis**

**Table 47: Growth percentages of S26**

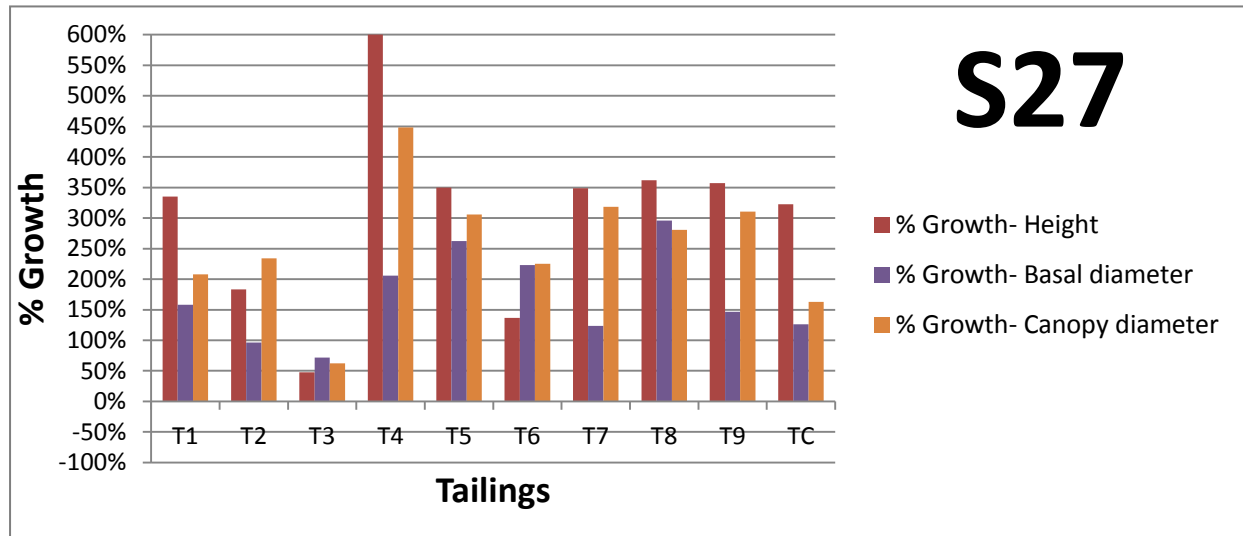
S26	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	117%	156%	339%
T2	176%	39%	49%
T3	70%	49%	124%
T4	334%	118%	359%
T5	136%	139%	177%
T6	62%	23%	183%
T7	88%	90%	278%
T8	151%	104%	226%
T9	148%	118%	423%
TC	386%	390%	413%



**Figure 60: Graph of S26 with tailings on the x-axis, indicating growth percentage of S26 on the y-axis**

**Table 48: Growth percentages of S27**

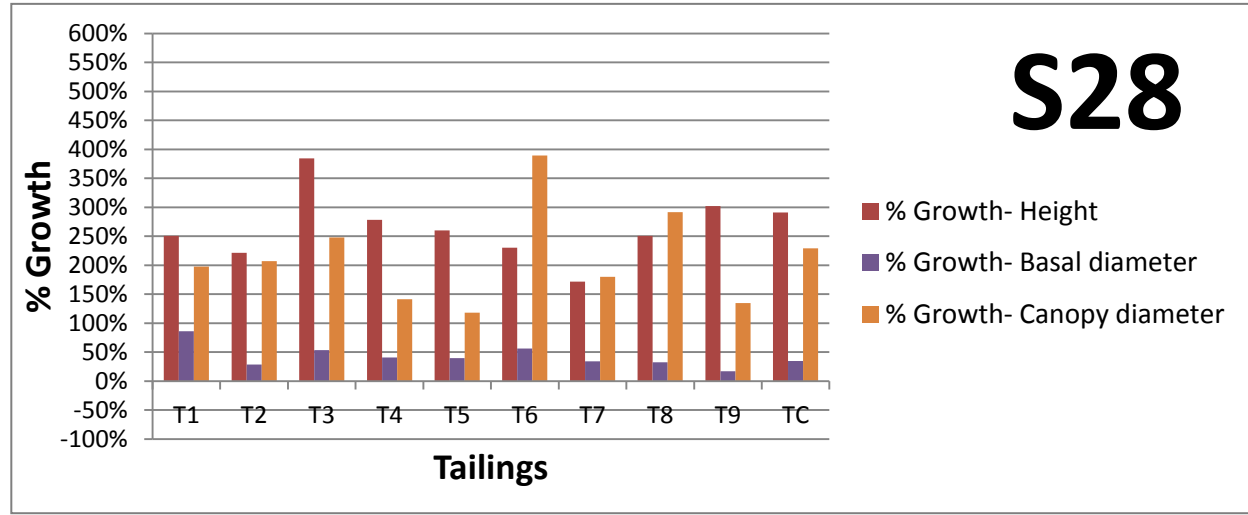
S27	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	335%	158%	208%
T2	183%	96%	234%
T3	0%	0%	0%
T4	600%	206%	448%
T5	350%	262%	306%
T6	137%	223%	225%
T7	349%	123%	318%
T8	362%	296%	281%
T9	357%	147%	310%
TC	323%	126%	163%



**Figure 61: Graph of S27 with tailings on the x-axis, indicating growth percentage of S27 on the y-axis**

**Table 49: Growth percentages of S28**

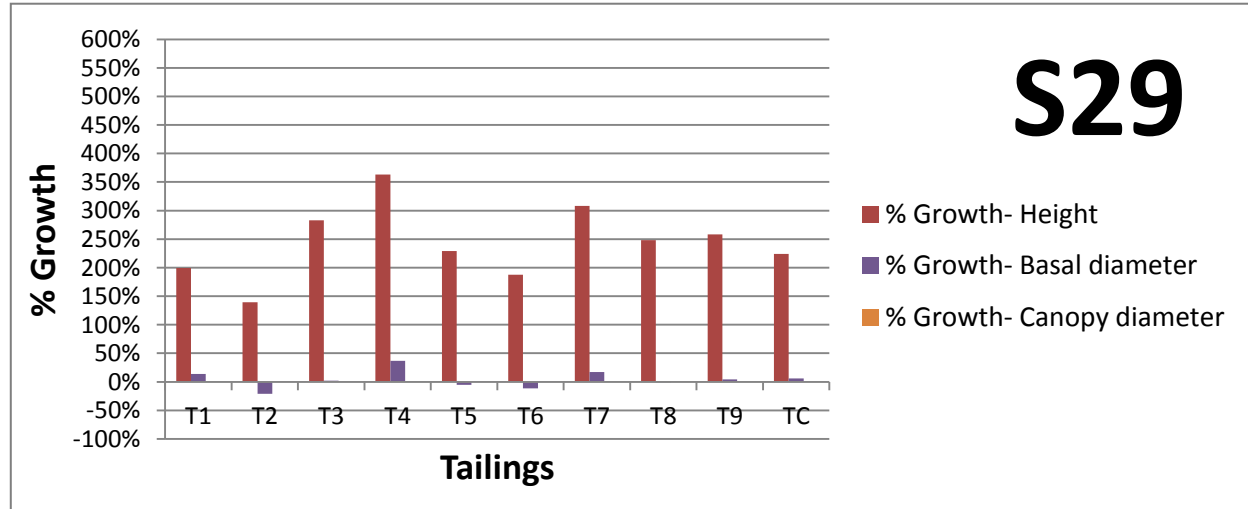
S28	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	250%	86%	197%
T2	221%	29%	207%
T3	384%	53%	248%
T4	278%	41%	141%
T5	260%	40%	118%
T6	230%	56%	389%
T7	172%	34%	180%
T8	251%	33%	292%
T9	302%	17%	134%
TC	291%	35%	229%



**Figure 62: Graph of S28 with tailings on the x-axis, indicating growth percentage of S28 on the y-axis**

**Table 50: Growth percentages of S29**

S29	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1	199%	14%	0%
T2	139%	-21%	0%
T3	283%	2%	0%
T4	363%	37%	0%
T5	229%	-5%	0%
T6	188%	-12%	0%
T7	308%	17%	0%
T8	248%	0%	0%
T9	258%	4%	0%
TC	224%	6%	0%



**Figure 63: Graph of S29 with tailings on the x-axis, indicating growth percentage of S29 on the y-axis**

## 4.5 Final index tables

Table 51: Final index table with colours attributed according to standard deviation

	T1	T2	T3	T4	T5	T6	T7	T8	T9	TC	AVG
S01	5	3	3	5	3	1	8	5	5	4	4.13
S02	6	5	5	5	5	3	7	5	3	5	4.89
S03	2	2	2	3	3	0	3	2	2	3	2.12
S04	3	3	6	4	4	2	3	3	3	3	3.22
S05	0	1	2	0	1	2	2	1	2	2	1.47
S06	3	3	3	3	3	2	3	3	3	3	2.93
S07	3	4	4	4	3	3	4	2	5	4	3.60
S08	3	2	2	3	3	0	3	3	3	3	2.35
S09	5	3	4	4	3	0	7	6	6	5	4.29
S10	3	4	3	4	4	2	5	3	2	3	3.23
S11	3	1	0	4	2	2	5	0	4	1	2.26
S12	1	2	3	1	2	0	2	1	1	2	1.52
S13	0	0	0	0	-3	3	5	2	3	2	1.16
S15	3	2	1	2	3	1	5	1	3	0	2.13
S17	4	0	2	3	4	2	2	4	5	0	2.62
S19	2	5	3	2	3	1	9	3	2	1	3.14
S23	7	4	8	8	8	8	7	5	4	4	6.34
S25	4	5	4	5	3	6	3	4	3	4	4.08
S26	6	2	4	6	5	4	5	5	6	9	5.23
S27	7	6	3	10	8	6	7	9	8	7	6.98
S28	6	5	6	5	5	7	4	6	5	6	5.61
S29	6	4	8	9	7	6	9	7	8	7	7.18
AVG	3.71	3.11	3.51	4.07	3.59	2.74	4.81	3.74	3.83	3.47	3.66

FINAL INDEX WITH STANDARD DEVIATION AND AVERAGE					
Average 3.6581					
Standard deviation (STDV) 2.2031					
	Within two STDV	With in one STDV	Average	With in one STDV	Within two STDV
Value	-0.7481	1.4550	3.6581	5.8612	8.0643
Between	-0.7481 and 1.4550	1.4551 and 3.6581	3.6582 and 5.8612	5.8613 and 8.0643	8.0644 and larger
Number in category	25	101	55	29	10
% of the data in category	11%	46%	25%	13%	5%

Table 52: Final index table of grasses with colours attributed according to standard deviation

	T1	T2	T3	T4	T5	T6	T7	T8	T9	TC	AVG
S10	3	4	3	4	4	2	5	3	2	3	3.23
S11	3	1	0	4	2	2	5	0	4	1	2.26
S13	0	0	0	0	0	3	5	2	3	2	1.41
S15	3	2	1	2	3	1	5	1	3	0	2.13
S17	4	0	2	3	4	2	2	4	5	0	2.62
S19	2	5	3	2	3	1	9	3	2	1	3.14
S25	4	5	4	5	3	6	3	4	3	4	4.08
S29	6	4	8	9	7	6	9	7	8	7	7.18
AVG	3.07	2.63	2.89	3.60	3.28	2.78	5.33	3.10	3.61	2.28	3.26

GRASSES - FINAL INDEX WITH STANDARD DEVIATION AND AVERAGE					
Average 3.2563					
Standard deviation (STDV) 2.2492					
	Within two STDV	With in one STDV	Average	With in one STDV	Within two STDV
Value	-1.2421	1.0071	3.2563	5.5054	7.7546
Between	-1.2421 and 1.0071	1.0072 and 3.2563	3.2564 and 5.5054	5.5055 and 7.7546	7.7547 and larger
Number in category	11	34	24	7	4
% of the data in category	14%	43%	30%	9%	5%

**Table 53: Final index table of trees with colours attributed according to standard deviation**

<b>TREES - FINAL INDEX WITH STANDARD DEVIATION AND AVERAGE</b>											
	T1	T2	T3	T4	T5	T6	T7	T8	T9	TC	AVG
S01	5	3	3	5	3	1	8	5	5	4	4.13
S02	6	5	5	5	5	3	7	5	3	5	4.89
S03	2	2	2	3	3	0	3	2	2	3	2.12
S04	3	3	6	4	4	2	3	3	3	3	3.22
S05	0	1	2	0	1	2	2	1	2	2	1.47
S06	3	3	3	3	3	2	3	3	3	3	2.93
S07	3	4	4	4	3	3	4	2	5	4	3.60
S08	3	2	2	3	3	0	3	3	3	3	2.35
S09	5	3	4	4	3	0	7	6	6	5	4.29
S12	1	2	3	1	2	0	2	1	1	2	1.52
S23	7	4	8	8	8	8	7	5	4	4	6.34
S26	6	2	4	6	5	4	5	5	6	9	5.23
S27	7	6	3	10	8	6	7	9	8	7	6.98
S28	6	5	6	5	5	7	4	6	5	6	5.61
AVG	4.08	3.38	3.87	4.34	3.94	2.71	4.52	4.11	3.95	4.15	3.91

Average 3.9056
Standard deviation (STDV) 2.1073

	Within two STDV	With in one STDV	Average	With in one STDV	Within two STDV
Value	-0.3091	1.7983	3.9056	6.0130	8.1203

Between	-0.3091 ans 1.7983	1.7984 and 3.9056	3.9057 and 6.0130	6.0131 and 8.1203	8.1204 and larger
Number in category	17	60	39	18	6
% of the data in category	12%	43%	28%	13%	4%

#### 4.5.1 Discussion of the index table for grasses

The index table of the grasses (Table 52) shows an average value of 3.26. The standard deviation ( $\sigma$ ) of the data is 2.2492. The distribution of the data from [avg. -  $2\sigma$ ] to [avg. +  $2\sigma$ ] is a bell curve.

Four species scored individual averages (the average taken of all values the specific species scored on all growth mediums) close to or above the average of the entire index table. These species were S10, *Vetiveria zizanioides* (avg. of 3.23), S19, *Themeda triandra* (3.14), S25, *Cymbopogon excavatus* (4.08) and S29, *Psathyrostachys junceus* (7.18).

The averages of the remaining species S11 (*Bambusa glaucescens*), S13 (*Schoenoplectus acutus*), S15 (*Hyparrhenia hirta*) and S17 (*Cynodon dactylon*) were all within range of [avg. -  $\sigma$ ].

The species that did not survive the trial were left out of the table (S14, S16, S18 and S20). S21 was the same variant of *Cymbopogon excavatus* as S25.

In the case of S10, only two values were below average and below the value on the control soil. They are T6 and T9, i.e. the two types of coal tailings. The stress factors exhibited primarily by S10 in the different coal tailings were necrotic plant tissue (dead leaves) and in some cases chlorosis (yellow discoloration).

Individually, S11 scored well on the gypsum tailings (T1), platinum- (T4), fluorspar (T7) and fine coal- (T9). The lowest scores were on the two types of gold tailings T2 and T3, andalusite- (T8) and the control. Two stress factors were exhibited by S11: chlorosis and dead leaf tips. These stress factors were most common in acidic mediums.

The index table shows zero values for S13 (*Schoenoplectus acutus*) on T1 to T5. This is due to a gap in the data. No initial growth measurements were recorded for S13 on the first five tailings and therefore index values could not be calculated. On the remaining tailings and the control, however, S13 showed acceptable results. S13 scored a value of three on both types of coal tailings, which is higher than the value scored on the control soil (two). S13 scored an above average score of five on the fluorspar tailings (T7). The dominant stress factors exhibited by S13 were dead grass tips and stunted growth in the case of T8.

S15 (*Hyparrhenia hirta*), S17 (*Cynodon dactylon*) and S19 (*Themeda triandra*) exhibited very few plant stress factors. S15 and S19 showed isolated occurrences of purple discoloration but not enough to form a visible trend. The index values of these species were influenced by winter seasons in which these grasses are dormant. This needs to be taken into consideration when evaluating the growth of these species and does not necessarily indicate failed trials.

S25 (*Cymbopogon excavatus*) exhibited good growth on all tailings as well as on the control soil, with minimum plant stress factors visible.

S29 (*Psathyrostachys junceus*) exhibited excellent growth on all tailings as well as on the control soil, with almost no plant stress factors visible. This was the grass species with the

highest average index score. This species shows the most potential for rehabilitation of a wide range of tailings materials.

#### 4.5.2 Discussion of the index table for trees

The index table of the trees (Table 53) shows an average value of 3.91. The standard deviation ( $\sigma$ ) of the data is 2.1073. The distribution of the data from [avg. -  $2\sigma$ ] to [avg. +  $2\sigma$ ] is a bell curve.

Seven species scored values (the average taken of all values the specific species scored on all growth mediums) above the average of the entire index table. These species were S1, *Acacia caffra* (avg. of 4.13), S2, *Acacia karroo* (4.89), S9, *Eucalyptus mcarthurii* (4.29), S23, *Atriplex nummularia* (6.34), S26, *Grewia flava* (5.23), S27, *Diospyros lycioides* (6.72) and S28, *Sericea lespedeza* (5.61).

Two other species scored values close to the average of the index table and proved to be viable for establishment on various tailings. These species are S4, *Searsia pyroides* (3.22) and S7, *Combretum erythrophylum* (3.60).

The averages of the remaining species were below the average of the table. On none of the tailings did any of these species score an above average result. These species include:

- S3 - *Searsia lancea* (avg. of 2.12)
- S5 - *Buddleja saligna* (1.47)
- S6 - *Olea europaea* (2.93)
- S8 - *Celtis africana* (2.35)
- S12 - *Asparagus larycinus* (1.52)

S3 exhibited necrosis of leaf tissue and chlorosis on the gypsum- (T1), gold- (T2 and T3) and fine coal tailings (T9). On the coal discard tailings (T6) there were no surviving plants of S3. The control plants also exhibited chlorosis of leaves and necrotic spots.

S5 had very few surviving plants on all the tailings except fluorspar (T7). On all tailings, S5 exhibited necrotic branches and very few healthy leaves. Leaf tissue was necrotic and in many cases leaves were small and deformed. Some plants started resprouting after  $\pm 12$  months. On the control soil, S5 also exhibited necrosis but all plants seemed to be resprouting at the base.

S6 exhibited chlorosis and necrosis of leaf tissue on the gold tailings (T2 and T3). Some chlorosis also occurred on the platinum tailings (T4). On the kimberlite tailings (T5) the plants exhibited small and deformed leaves or very few to no leaves at all. On both types of coal tailings S6 exhibited chlorosis and necrosis of leaves and branches. On the andalusite tailings, the plants' growth appeared to be stunted and leaves were small and curled or not present at all. All plants of S6 planted in the control soil were healthy.

On all nine tailings and the control soil, S8 exhibited necrosis of leaf tissue, mostly around the edges and tips. Chlorosis of leaves was also common. The plants also had very few

leaves in most cases, even in summer; therefore the deciduous nature of the species was not the cause for the loss of leaves.

S12 exhibited severe stress factors on all the tailings, except the gold tailings (T3) and the control soil. The mortality of S12 was exceptionally low, with many plants not surviving the trial. The stress factors that were exhibited included chlorosis of leaves, as well as extensive necrosis of branches and leaves.

Two species of trees failed conclusively in that all plants died during the trial. These species were S22, *Pavetta edentula*, and S24, *Portulacaria afra*. S22 did not survive the winter of 2012, whilst S24 did not survive the winter of 2013. Both species were affected by subzero temperatures and frost.

## Chapter 5 - Conclusion and recommendations

Table 54 and Table 55 contain the grasses and trees that proved successful for establishment on the different tailings, respectively. These species all scored above the average of the respective index tables for grasses or trees and are therefore recommended for rehabilitation of the specific tailings.

**Table 54: Recommended grass species for establishment on various tailings**

Tailings	Grasses names	
<b>T1</b>	<i>Cynodon dactylon</i>	Couch grass
	<i>Cymbopogon excavatus</i>	Broad leaf turpentine grass
	<i>Psathyrostachys junceus</i>	Russian wildrye grass
<b>T2</b>	<i>Vetiveria zizanioides</i>	Vetiver
	<i>Themeda triandra</i>	Red grass
	<i>Cymbopogon excavatus</i>	Broad leaf turpentine grass
	<i>Psathyrostachys junceus</i>	Russian wildrye grass
<b>T3</b>	<i>Vetiveria zizanioides</i>	Vetiver
	<i>Themeda triandra</i>	Red grass
	<i>Cymbopogon excavatus</i>	Broad leaf turpentine grass
	<i>Psathyrostachys junceus</i>	Russian wildrye grass
<b>T4</b>	<i>Vetiveria zizanioides</i>	Vetiver
	<i>Bambusa glaucescens</i>	Hedge bamboo
	<i>Cymbopogon excavatus</i>	Broad leaf turpentine grass
	<i>Psathyrostachys junceus</i>	Russian wildrye grass
<b>T5</b>	<i>Vetiveria zizanioides</i>	Vetiver
	<i>Cynodon dactylon</i>	Couch grass
	<i>Psathyrostachys junceus</i>	Russian wildrye grass
<b>T6</b>	<i>Cymbopogon excavatus</i>	Broad leaf turpentine grass
	<i>Psathyrostachys junceus</i>	Russian wildrye grass
<b>T7</b>	<i>Vetiveria zizanioides</i>	Vetiver
	<i>Bambusa glaucescens</i>	Hedge bamboo
	<i>Schoenoplectus acutus</i>	Hardstem Bulrush
	<i>Hyparrhenia hirta</i>	Thatch grass
	<i>Themeda triandra</i>	Red grass
	<i>Psathyrostachys junceus</i>	Russian wildrye grass
<b>T8</b>	<i>Vetiveria zizanioides</i>	Vetiver
	<i>Cynodon dactylon</i>	Couch grass
	<i>Cymbopogon excavatus</i>	Broad leaf turpentine grass
	<i>Psathyrostachys junceus</i>	Russian wildrye grass
<b>T9</b>	<i>Bambusa glaucescens</i>	Hedge bamboo
	<i>Cynodon dactylon</i>	Couch grass
	<i>Psathyrostachys junceus</i>	Russian wildrye grass
<b>TC</b>	<i>Cymbopogon excavatus</i>	Broad leaf turpentine grass
	<i>Psathyrostachys junceus</i>	Russian wildrye grass

**Table 55: Recommended tree species for establishment on various tailings**

<b>Tailings</b>	<b>Tree names</b>	
<b>T1</b>	<i>Acacia caffra</i>	Hook thorn
	<i>Acacia karroo</i>	Sweet thorn
	<i>Eucalyptus macarthurii</i>	Eucalyptus
	<i>Atriplex nummularia</i>	Old man's Saltbush
	<i>Grewia flava</i>	Velvet raisin
	<i>Diospyros lycioides</i>	<i>Transvaal bluebush</i>
	<i>Sericea lespedeza</i>	Poor man's lucerne
<b>T2</b>	<i>Acacia karroo</i>	Sweet thorn
	<i>Searsia pyroides</i>	Currant
	<i>Combretum erythrophylum</i>	River bushwillow
	<i>Atriplex nummularia</i>	Old man's Saltbush
	<i>Diospyros lycioides</i>	<i>Transvaal bluebush</i>
	<i>Sericea lespedeza</i>	Poor man's lucerne
<b>T3</b>	<i>Acacia karroo</i>	Sweet thorn
	<i>Combretum erythrophylum</i>	River bushwillow
	<i>Eucalyptus macarthurii</i>	Eucalyptus
	<i>Atriplex nummularia</i>	Old man's Saltbush
	<i>Sericea lespedeza</i>	Poor man's lucerne
<b>T4</b>	<i>Acacia caffra</i>	Hook thorn
	<i>Acacia karroo</i>	Sweet thorn
	<i>Combretum erythrophylum</i>	River bushwillow
	<i>Eucalyptus macarthurii</i>	Eucalyptus
	<i>Atriplex nummularia</i>	Old man's Saltbush
	<i>Grewia flava</i>	Velvet raisin
	<i>Diospyros lycioides</i>	<i>Transvaal bluebush</i>
	<i>Sericea lespedeza</i>	Poor man's lucerne
<b>T5</b>	<i>Acacia karroo</i>	Sweet thorn
	<i>Atriplex nummularia</i>	Old man's Saltbush
	<i>Grewia flava</i>	Velvet raisin
	<i>Diospyros lycioides</i>	<i>Transvaal bluebush</i>
	<i>Sericea lespedeza</i>	Poor man's lucerne
<b>T6</b>	<i>Atriplex nummularia</i>	Old man's Saltbush
	<i>Grewia flava</i>	Velvet raisin
	<i>Diospyros lycioides</i>	<i>Transvaal bluebush</i>
	<i>Sericea lespedeza</i>	Poor man's lucerne
<b>T7</b>	<i>Acacia caffra</i>	Hook thorn
	<i>Acacia karroo</i>	Sweet thorn
	<i>Combretum erythrophylum</i>	River bushwillow
	<i>Eucalyptus macarthurii</i>	Eucalyptus
	<i>Atriplex nummularia</i>	Old man's Saltbush
	<i>Grewia flava</i>	Velvet raisin
	<i>Diospyros lycioides</i>	<i>Transvaal bluebush</i>
	<i>Sericea lespedeza</i>	Poor man's lucerne

<b>T8</b>	<i>Acacia caffra</i>	Hook thorn
	<i>Acacia karroo</i>	Sweet thorn
	<i>Eucalyptus macarthurii</i>	Eucalyptus
	<i>Atriplex nummularia</i>	Old man's Saltbush
	<i>Grewia flava</i>	Velvet raisin
	<i>Diospyros lycioides</i>	<i>Transvaal bluebush</i>
	<i>Sericea lespedeza</i>	Poor man's lucerne
<b>T9</b>	<i>Acacia caffra</i>	Hook thorn
	<i>Combretum erythrophyllum</i>	River bushwillow
	<i>Eucalyptus macarthurii</i>	Eucalyptus
	<i>Atriplex nummularia</i>	Old man's Saltbush
	<i>Grewia flava</i>	Velvet raisin
	<i>Diospyros lycioides</i>	<i>Transvaal bluebush</i>
	<i>Sericea lespedeza</i>	Poor man's lucerne
<b>TC</b>	<i>Acacia karroo</i>	Sweet thorn
	<i>Eucalyptus macarthurii</i>	Eucalyptus
	<i>Atriplex nummularia</i>	Old man's Saltbush
	<i>Grewia flava</i>	Velvet raisin
	<i>Diospyros lycioides</i>	<i>Transvaal bluebush</i>
	<i>Sericea lespedeza</i>	Poor man's lucerne

The most important objective of this study was to develop a method to identify plants that will survive when established in the various tailings and therefore plant species that can be expected to survive when used during rehabilitation. The amelioration of the tailings and the watering of the plants were done using standard procedures used in TSF rehabilitation. For this, the index table method was developed and can be recreated again for further trials. The species in Table 54 and 55 are recommended to be used for rehabilitation of the various tailings and can be considered for use in the field.

Four of the species in this trial was researched by Faul & Van Deventer (2014). The chlorophyll fluorescence of these species and the correlation thereof with plant stresses were researched. The parameters used were Vitality Index ( $PI_{ABS}$ ) and Fluorescence Intensity (FI). If the species with the highest  $PI_{ABS}$  and FI is also the species that showed the best growth potential according to the index table in this study, it can be assumed that the results in the index table are accurate.

The species were *Grewia flava* (S26), *Diospyros lycioides* (S27), *Sericea lespedeza* (S28) and *Psatyrostachys junceus* (S29). The plants were established in the same mine tailings as discussed in this paper.

In their study, Faul & Van Deventer (2014) measured chlorophyll fluorescence with the HandyPEA handheld device. The HandyPEA computer program was used to transfer and sort the data, whereafter the Biolyzer program was used to calculate OJIP transients. The OJIP transients indicate the fluorescence intensity in the plants. The data was used to compile line graphs which show the fluorescence intensity of each plant species on the different tailings. The line curves of the different species were normalized to the species with

the highest fluorescence intensity, to be able to identify certain peaks, illustrated in Figure 64 (Faul & Van Deventer, 2014). The peaks indicate the following:

- K-peak = The K-peak suggests the inefficient oxidation of water at the Oxygen Evolving Complex.
- J-peak = The J-peak suggests that electrons cannot move further down the electron transport chain than  $Q_A^-$ .
- I-peak = The I-peak suggests that electrons cannot move further down the electron transport chain than  $Q_B^-$ .
- G-peak = The G-peak suggests that the accumulation at  $Q_BH_2$ , can be attributed to decrease in the rate in the reduction of the end electron acceptor.

(Faul & Van Deventer, 2014)

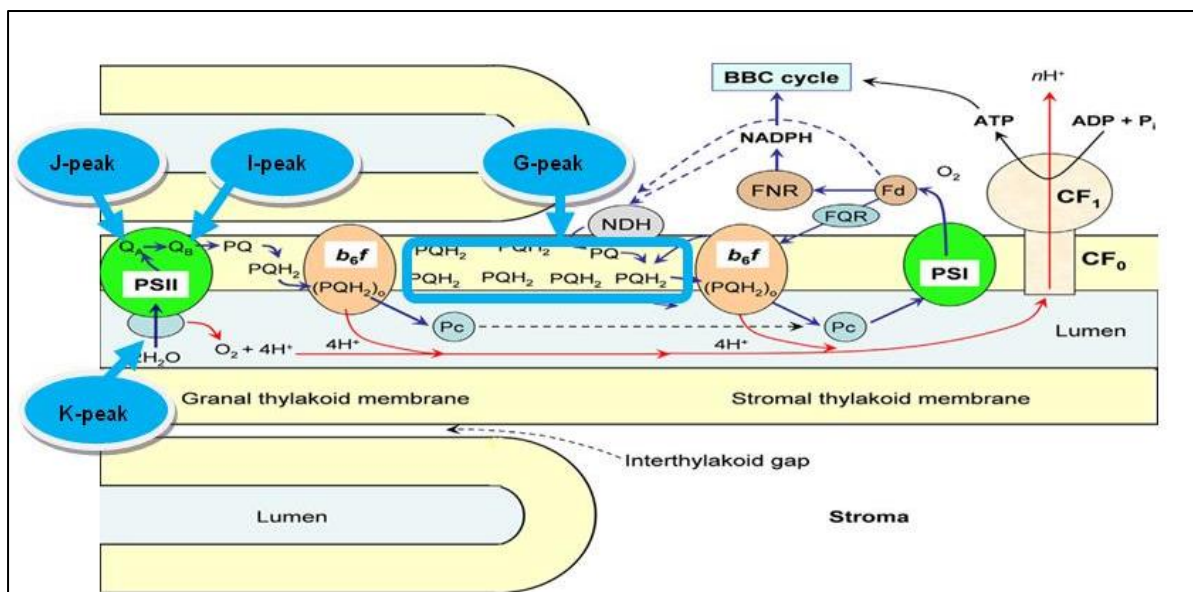


Figure 64: The electron transport chain in the chloroplast

Figure 67 (Tikhonoc et al., (2014 [as cited by Faul & Van Deventer, 2014]) illustrates the electron transport chain in the chloroplasts of plants. The locations of the different peaks inside the chloroplast are indicated as well. The results of the research are summarized in Table 56.

Table 56: Chlorophyll fluorescence peaks indicating plant physiological stresses

	<i>Grewia flava</i>	<i>Diospyros lycioides</i>	<i>Sericea lespedeza</i>	<i>Psathyrostachys junceus</i>
<b>Gypsum</b>	J-peak	J-peak	K-peak	Normalised
<b>Gold with &lt;1% pyrite</b>	J-peak	J-peak	K-peak and J-peak	Normalised
<b>Gold with &gt;2% pyrite</b>	I-peak	I-peak	I-peak	Normalised
<b>Platinum</b>	J-peak	J-peak	K-peak and G-peak	Normalised
<b>Kimberlite</b>	J-peak	J-peak	K-peak	Normalised
<b>Coal discard tailings</b>	J-peak	J-peak	K-peak	Normalised
<b>Fluorspar</b>	J-peak	J-peak	K-peak and J-peak	Normalised
<b>Andalusite</b>	J-peak	J-peak	J-peak	Normalised
<b>Fine Coal tailings</b>	J-peak	J-peak	K-peak and J-peak	Normalised

The conclusion drawn by Faul & Van Deventer (2014) regarding the plant species that were most successful under the different physiological stresses is summarized in Table 57.

**Table 57: Plant species that were most successful under different physiological stresses**

	<b>Vitality index (PI<sub>ABS</sub>)</b>	<b>Fluorescence Intensity</b>
<b>Gypsum</b>	<i>Psathyrostachys junceus</i>	<i>Psathyrostachys junceus</i>
<b>Gold with &lt;1% pyrite</b>	<i>Grewia flava</i> <i>Psathyrostachys junceus</i>	<i>Psathyrostachys junceus</i> <i>Grewia flava</i>
<b>Gold with &gt;2% pyrite</b>	<i>Grewia flava</i> <i>Sericea lespedeza</i>	<i>Psathyrostachys junceus</i> <i>Sericea lespedeza</i>
<b>Platinum</b>	<i>Diospyros lycioides</i> <i>Psathyrostachys junceus</i>	<i>Psathyrostachys junceus</i> <i>Diospyros lycioides</i>
<b>Kimberlite</b>	<i>Psathyrostachys junceus</i>	<i>Psathyrostachys junceus</i>
<b>Coal discard</b>	<i>Psathyrostachys junceus</i>	<i>Psathyrostachys junceus</i>
<b>Fluorspar</b>	<i>Psathyrostachys junceus</i>	<i>Psathyrostachys junceus</i>
<b>Andalusite</b>	<i>Psathyrostachys junceus</i>	<i>Psathyrostachys junceus</i>
<b>Fine Coal tailings</b>	<i>Psathyrostachys junceus</i>	<i>Psathyrostachys junceus</i>

As can be seen from Table 57, *Psathyrostachys junceus* was identified overall as the species with the highest PI<sub>ABS</sub> and FI out of the four species. *Psathyrostachys* is also identified in the index table as the most suitable species for rehabilitation on the different tailings, with the highest average score. On the platinum tailings, S27, *Diospyros lycioides* indicated a high PI<sub>ABS</sub> and FI, which correlates well with the index table in which S27 scored 10 on this particular tailings (the highest score in the table). On the T3 gold tailings (>2% pyrite) *Sericea lespedeza* indicated high PI<sub>ABS</sub> and FI and on the index table it is the species with the second highest score on T3.

These correlations support the findings of this paper, however, *Grewia flava* (S26), achieved a high PI<sub>ABS</sub> on both gold tailings and high FI on the gold with the low pyrite content, whilst it is not identified by the index table as the most suitable species for rehabilitation. On T2 it scores below the average of the table and on T3 it scores slightly above. The raw data indicated that it was not the growth of the plants that had a negative impact but rather the mortality rate. 50% of the plants in the T2 material survived the full term of the trial and 75% survived in the T3 material.

To be able to measure the success of plant species in the rehabilitation process, it is proposed that the growth potential as described in this paper is assessed in tandem with the physiological health and stress factors of the plants, using chlorophyll fluorescence as described by Faul & Van Deventer.

## Chapter 6 - References

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## Appendix 1 - Additional growth data tables and graphs

Table 58: Growth percentages of T1, T2 and T3

<b>T1</b>	%Growth-Height	%Growth-Basal diameter	%Growth-Canopy diameter		<b>T2</b>	%Growth-Height	%Growth-Basal diameter	% Growth-Canopy diameter		<b>T3</b>	%Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T1-S01	79%	200%	95%		T2-S01	66%	98%	164%		T3-S01	126%	37%	8%
T1-S02	188%	251%	183%		T2-S02	140%	168%	145%		T3-S02	23%	302%	56%
T1-S03	64%	33%	32%		T2-S03	12%	45%	2%		T3-S03	3%	56%	-18%
T1-S04	10%	78%	2%		T2-S04	6%	72%	-4%		T3-S04	10%	584%	45%
T1-S05	-30%	9%	-12%		T2-S05	-11%	39%	-9%		T3-S05	-30%	47%	45%
T1-S06	41%	76%	35%		T2-S06	21%	98%	9%		T3-S06	40%	74%	23%
T1-S07	55%	69%	36%		T2-S07	82%	127%	49%		T3-S07	84%	158%	87%
T1-S08	18%	84%	58%		T2-S08	7%	19%	5%		T3-S08	21%	27%	-5%
T1-S09	65%	189%	122%		T2-S09	57%	76%	43%		T3-S09	55%	146%	95%
T1-S10	64%	0%	0%		T2-S10	66%	0%	0%		T3-S10	58%	0%	0%
T1-S11	60%	0%	0%		T2-S11	26%	0%	0%		T3-S11			
T1-S12	24%	5%	-18%		T2-S12	-5%	-3%	43%		T3-S12	46%	1%	16%
T1-S13					T2-S13					T3-S13			
T1-S15	26%	0%	0%		T2-S15	6%	0%	0%		T3-S15	-36%	0%	0%
T1-S17	84%	0%	0%		T2-S17					T3-S17	15%	0%	0%
T1-S19	12%	0%	0%		T2-S19	13/%	0%	0%		T3-S19	59%	0%	0%
T1-S23	238%	36%	414%		T2-S23	70%	93%	161%		T3-S23	214%	287%	345%
T1-S25	102%	0%	0%		T2-S25	152%	0%	0%		T3-S25	100%	0%	0%
T1-S26	117%	156%	339%		T2-S26	176%	39%	49%		T3-S26	70%	49%	124%
T1-S27	335%	158%	208%		T2-S27	183%	96%	234%		T3-S27	48%	71%	62%
T1-S28	250%	86%	197%		T2-S28	221%	29%	207%		T3-S28	384%	53%	248%
T1-S29	199%	14%	0%		T2-S29	139%	-21%	0%		T3-S29	283%	2%	0%

**Table 59: Growth percentages of T4, T5 and T6**

<b>T4</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter		<b>T5</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter		<b>T6</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T4-S01	115%	281%	133%		T5-S01	63%	121%	47%		T6-S01	-34%	83%	16%
T4-S02	91%	152%	287%		T5-S02	94%	208%	112%		T6-S02	78%	112%	53%
T4-S03	18%	40%	9%		T5-S03	0%	91%	11%		T6-S03	0%	0%	0%
T4-S04	29%	102%	83%		T5-S04	9%	119%	89%		T6-S04	-9%	35%	1%
T4-S05	-13%	30%	-27%		T5-S05	-9%	31%	-30%		T6-S05	-11%	8%	-34%
T4-S06	13%	111%	-8%		T5-S06	21%	114%	3%		T6-S06	-8%	38%	-13%
T4-S07	44%	188%	16%		T5-S07	18%	84%	-12%		T6-S07	-5%	120%	-32%
T4-S08	16%	53%	11%		T5-S08	-7%	26%	37%		T6-S08	0%	0%	0%
T4-S09	79%	193%	110%		T5-S09	-8%	69%	62%		T6-S09	6%	37%	-39%
T4-S10	71%	-74%	0%		T5-S10	79%	0%	0%		T6-S10	-15%	0%	0%
T4-S11	93%	0%	0%		T5-S11	28%	42%	53%		T6-S11	14%	-73%	-15%
T4-S12	23%	-17%	-12%		T5-S12	4%	-15%	-24%		T6-S12	-42%	-18%	-39%
T4-S13	36%	-81%	0%		T5-S13	0%	0%	0%		T6-S13	51%	0%	0%
T4-S15	36%	-81%	0%		T5-S15	44%	-84%	0%		T6-S15	-34%	-24%	0%
T4-S17	71%	0%	0%		T5-S17	105%	0%	0%		T6-S17	-25%		
T4-S19	-14%	0%	0%		T5-S19	38%	0%	0%		T6-S19	-10%	0%	0%
T4-S23	228%	285%	436%		T5-S23	141%	229%	442%		T6-S23	131%	257%	393%
T4-S25	154%	0%	0%		T5-S25	46%	1%	0%		T6-S25	176%	45%	0%
T4-S26	334%	118%	359%		T5-S26	136%	139%	177%		T6-S26	62%	23%	183%
T4-S27	600%	206%	448%		T5-S27	350%	262%	306%		T6-S27	137%	223%	225%
T4-S28	278%	41%	141%		T5-S28	260%	40%	118%		T6-S28	230%	56%	389%
T4-S29	363%	37%	0%		T5-S29	229%	-5%	0%		T6-S29	188%	-12%	0%

**Table 60: Growth percentages of T7, T8 and T9**

<b>T7</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter		<b>T8</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter		<b>T9</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
T7-S01	210%	295%	341%		T8-S01	64%	151%	211%		T9-S01	95%	227%	42%
T7-S02	116%	232%	83%		T8-S02	72%	105%	173%		T9-S02	0%	106%	35%
T7-S03	-1%	138%	1%		T8-S03	13%	84%	8%		T9-S03	-3%	29%	-37%
T7-S04	-4%	52%	25%		T8-S04	18%	117%	49%		T9-S04	17%	50%	16%
T7-S05	5%	30%	-1%		T8-S05	-46%	34%	5%		T9-S05	0%	91%	-26%
T7-S06	25%	87%	61%		T8-S06	21%	108%	12%		T9-S06	4%	132%	11%
T7-S07	59%	161%	82%		T8-S07	-24%	23%	24%		T9-S07	23%	353%	-26%
T7-S08	11%	38%	27%		T8-S08	98%	66%	8%		T9-S08	33%	31%	22%
T7-S09	420%	324%	0%		T8-S09	227%	355%	289%		T9-S09	102%	266%	151%
T7-S10	126%	0%	0%		T8-S10	61%	-64%	0%		T9-S10	3%	0%	0%
T7-S11	146%	0%	0%		T8-S11	-38%	0%	0%		T9-S11	66%	0%	0%
T7-S12	30%	11%	-21%		T8-S12	19%	23%	41%		T9-S12	4%	-4%	10%
T7-S13	124%	0%	0%		T8-S13	24%	-67%	0%		T9-S13	35%	-79%	0%
T7-S15	175%	0%	0%		T8-S15	23%	0%	0%		T9-S15	43%	-77%	0%
T7-S17	25%	0%	0%		T8-S17	110%	0%	0%		T9-S17	110%	0%	0%
T7-S19	297%	0%	0%		T8-S19	48%	0%	0%		T9-S19	28%	0%	0%
T7-S23	96%	168%	434%		T8-S23	55%	165%	179%		T9-S23	44%	38%	261%
T7-S25	41%	-39%	0%		T8-S25	120%	-9%	0%		T9-S25	43%	-7%	0%
T7-S26	88%	90%	278%		T8-S26	151%	104%	226%		T9-S26	148%	118%	423%
T7-S27	349%	123%	318%		T8-S27	362%	296%	281%		T9-S27	357%	147%	310%
T7-S28	172%	34%	180%		T8-S28	251%	33%	292%		T9-S28	302%	17%	134%
T7-S29	308%	17%	0%		T8-S29	248%	0%	0%		T9-S29	258%	4%	0%

**Table 61: Growth percentages of TC**

<b>TC</b>	% Growth-Height	% Growth-Basal diameter	% Growth-Canopy diameter
TC-S01	21%	233%	16%
TC-S02	140%	149%	62%
TC-S03	11%	62%	7%
TC-S04	-5%	69%	-13%
TC-S05	-11%	39%	12%
TC-S06	16%	89%	53%
TC-S07	83%	128%	41%
TC-S08	16%	37%	24%
TC-S09	89%	131%	113%
TC-S10	32%	0%	0%
TC-S11	-20%	0%	0%
TC-S12	21%	21%	-24%
TC-S13	0%	0%	0%
TC-S15	-44%	0%	0%
TC-S17	0%	0%	0%
TC-S19	-7%	0%	0%
TC-S23	63%	137%	218%
TC-S25	93%	-21%	0%
TC-S26	386%	390%	413%
TC-S27	323%	126%	163%
TC-S28	291%	35%	229%
TC-S29	224%	6%	0%

# T1

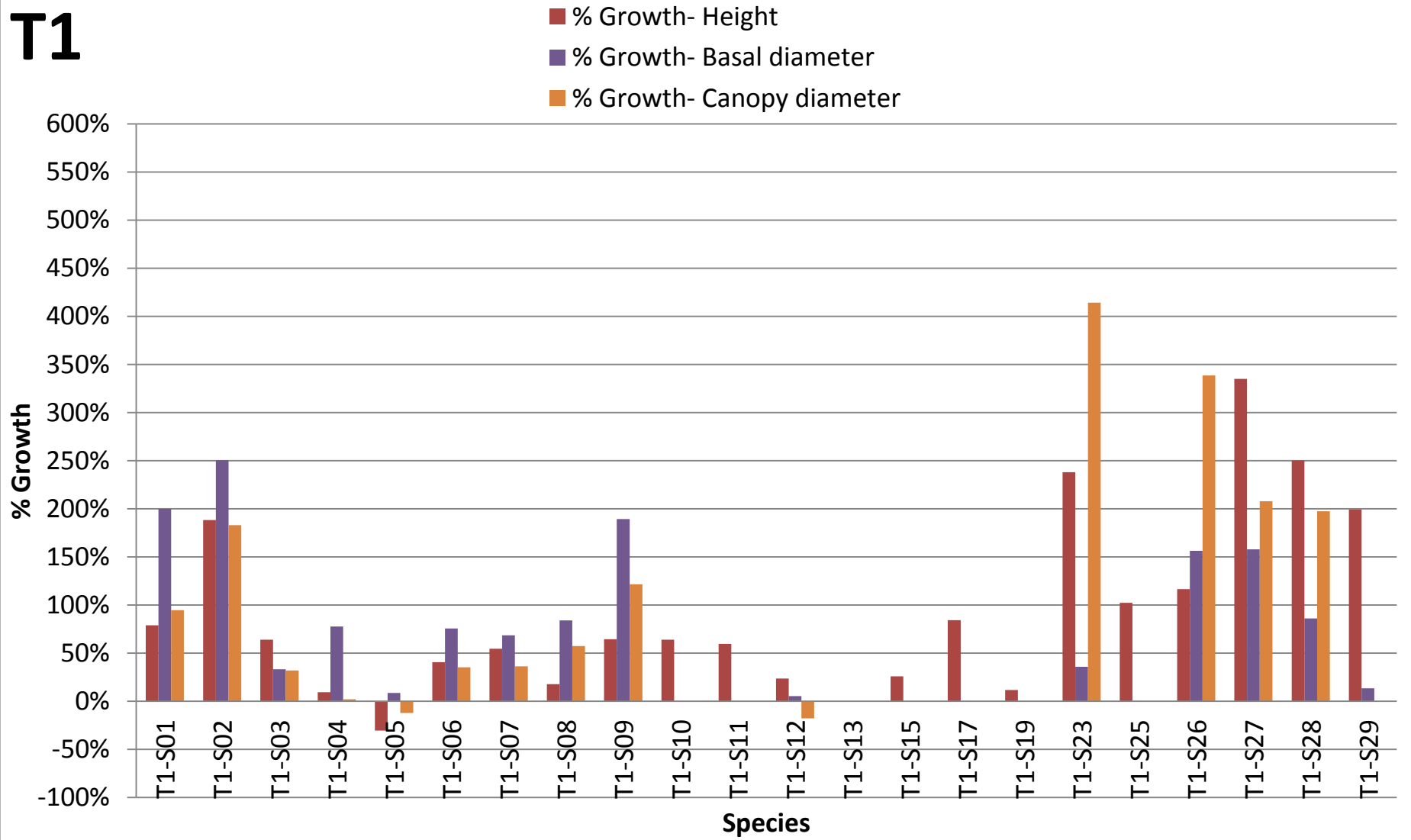


Figure 65: Graph of T1 with all species on the x-axis, indicating percentage increase in height, basal- and canopy diameter

# T2

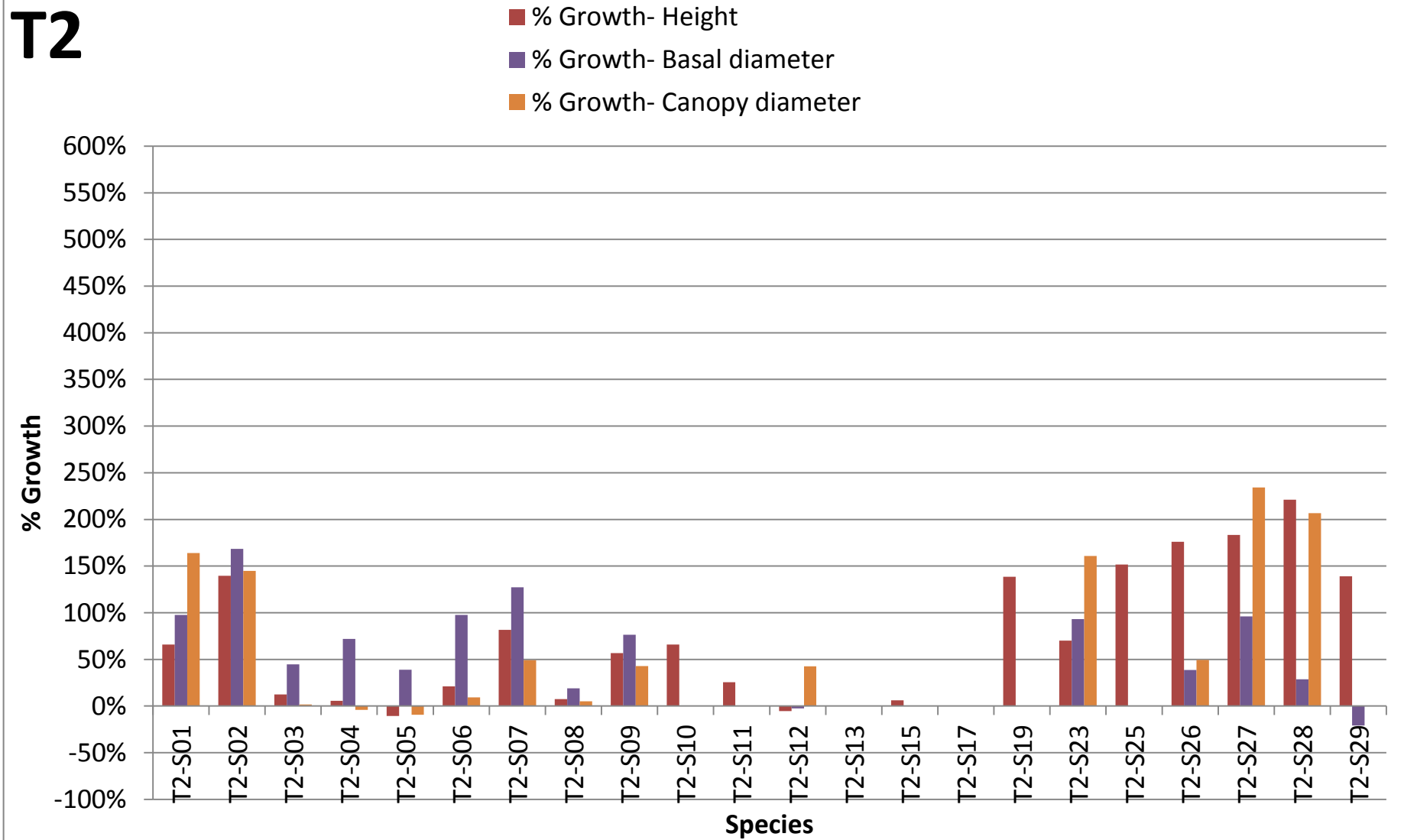


Figure 66: Graph of T2 with all species on the x-axis, indicating percentage increase in height, basal- and canopy diameter

# T3

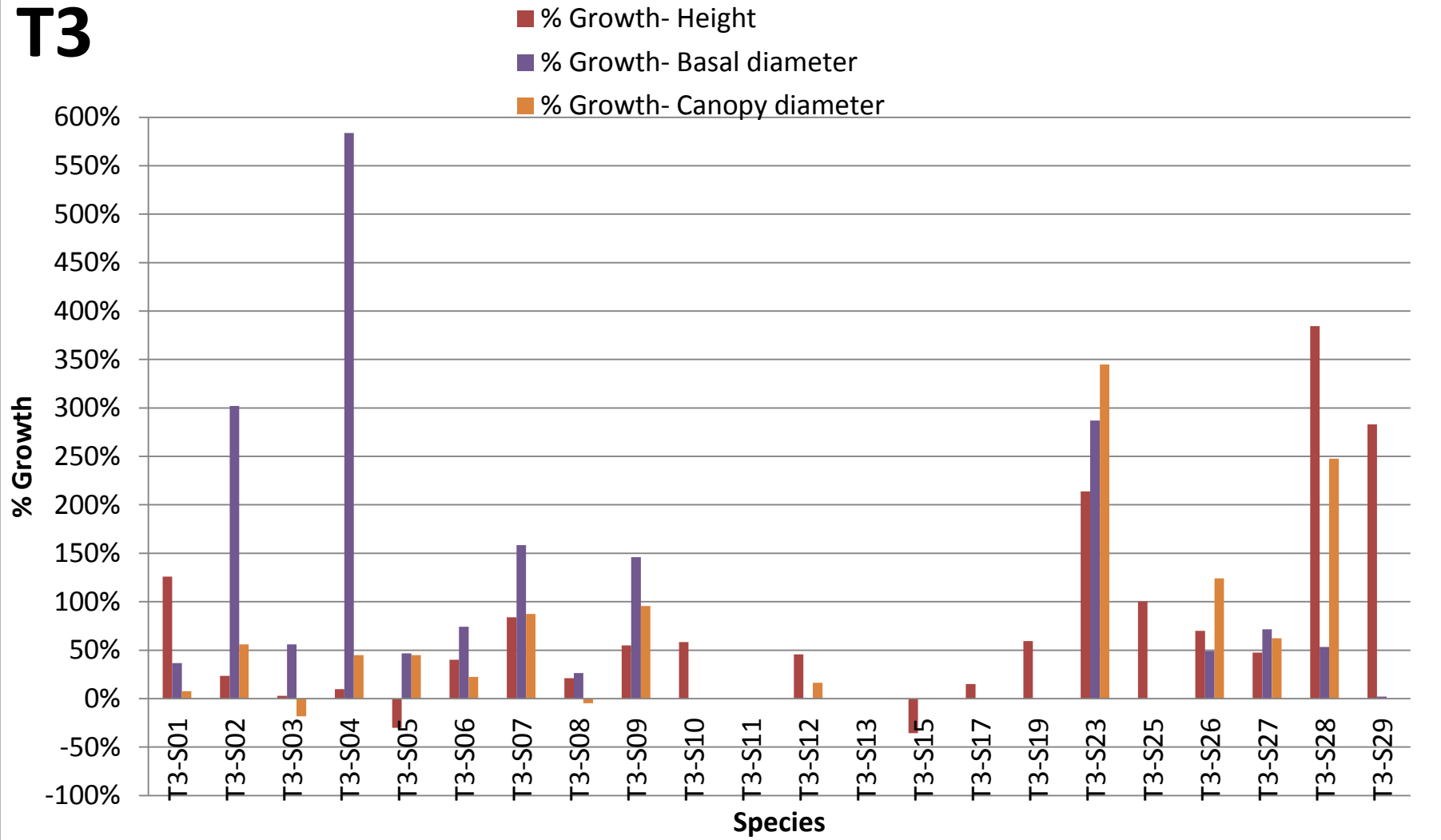


Figure 67: Graph of T3 with all species on the x-axis, indicating percentage increase in height, basal- and canopy diameter

# T4

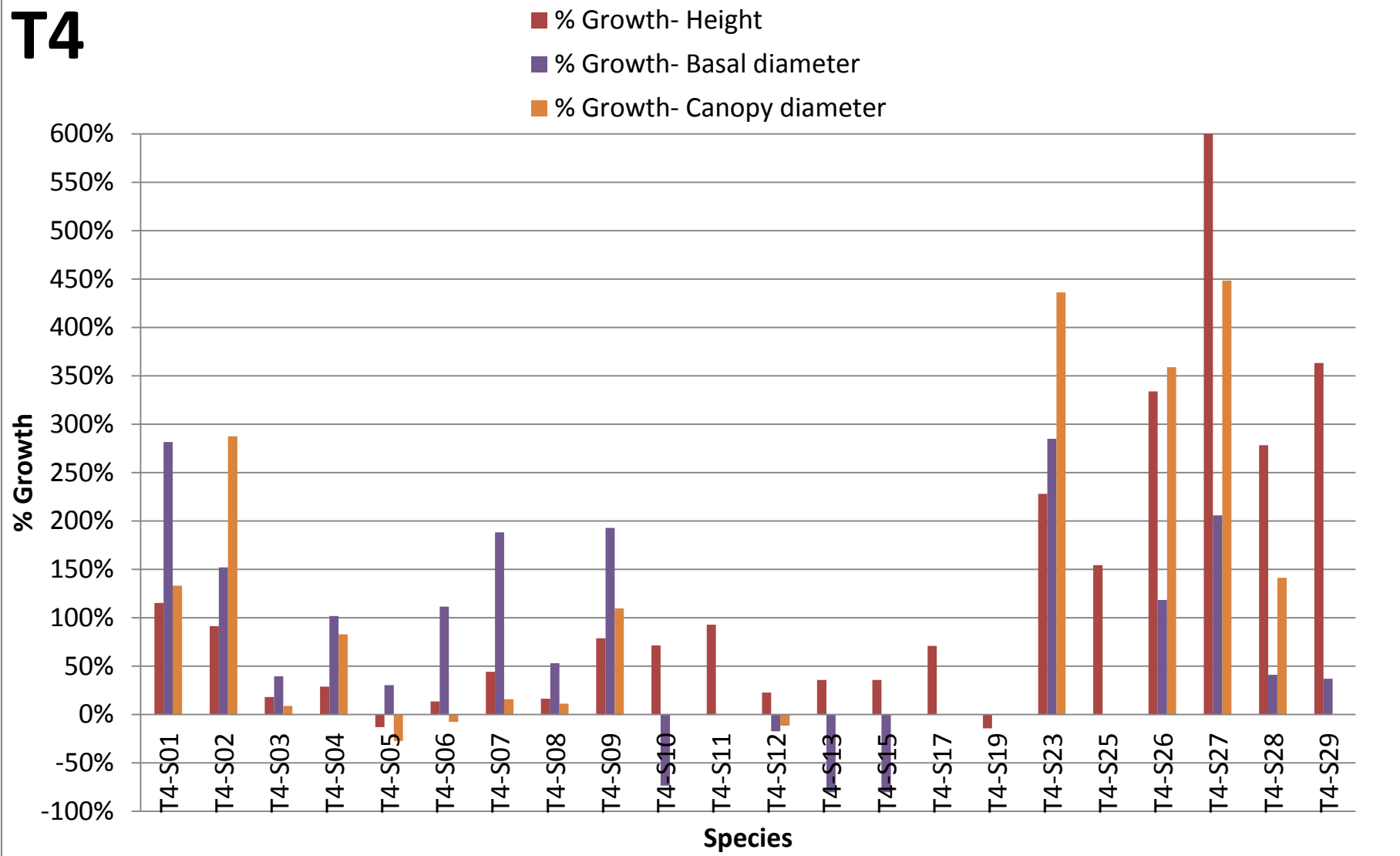


Figure 68: Graph of T4 with all species on the x-axis, indicating percentage increase in height, basal- and canopy diameter

# T5

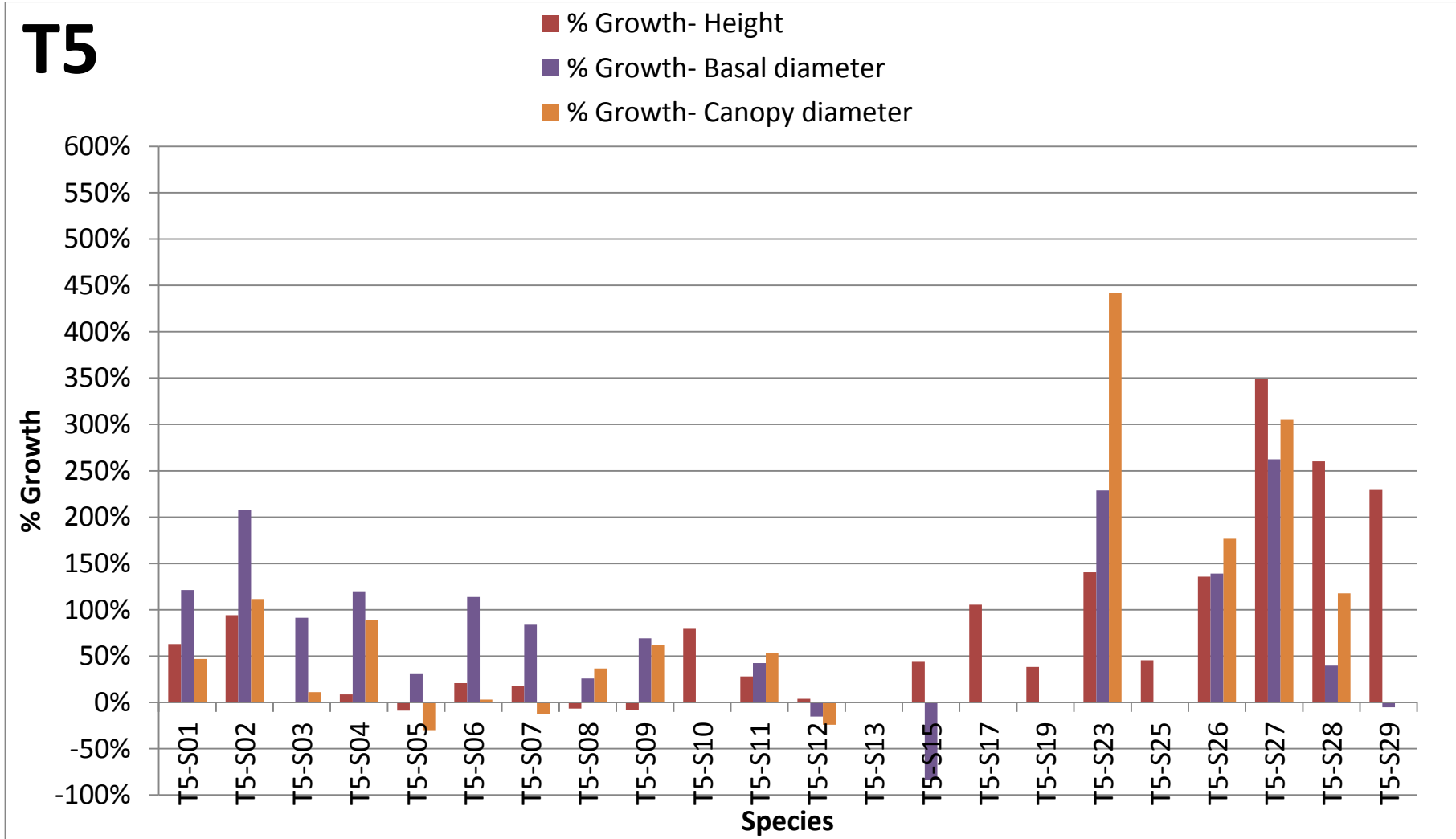


Figure 69: Graph of T5 with all species on the x-axis, indicating percentage increase in height, basal- and canopy diameter

# T6

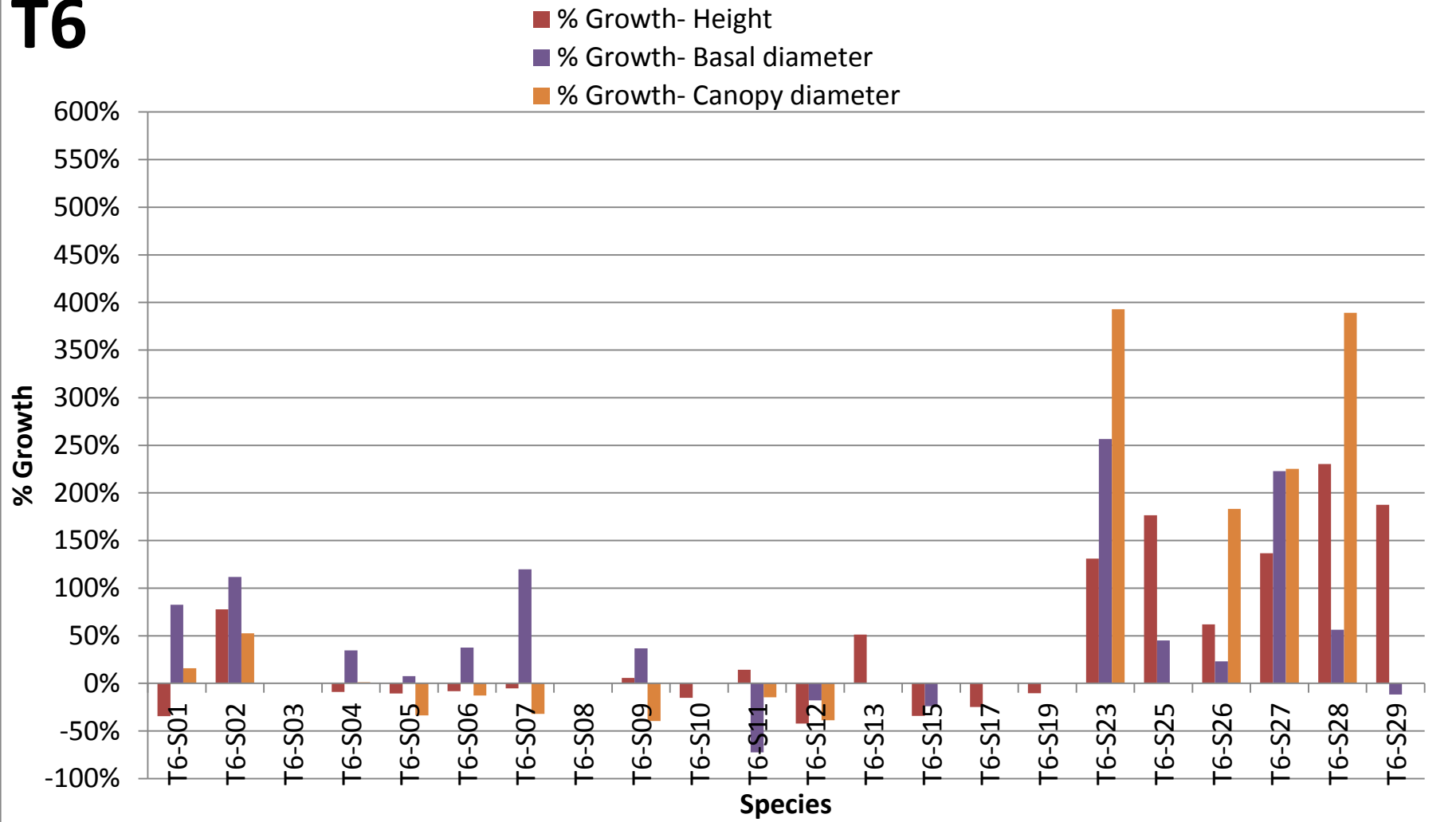


Figure 70: Graph of T6 with all species on the x-axis, indicating percentage increase in height, basal- and canopy diameter

# T7

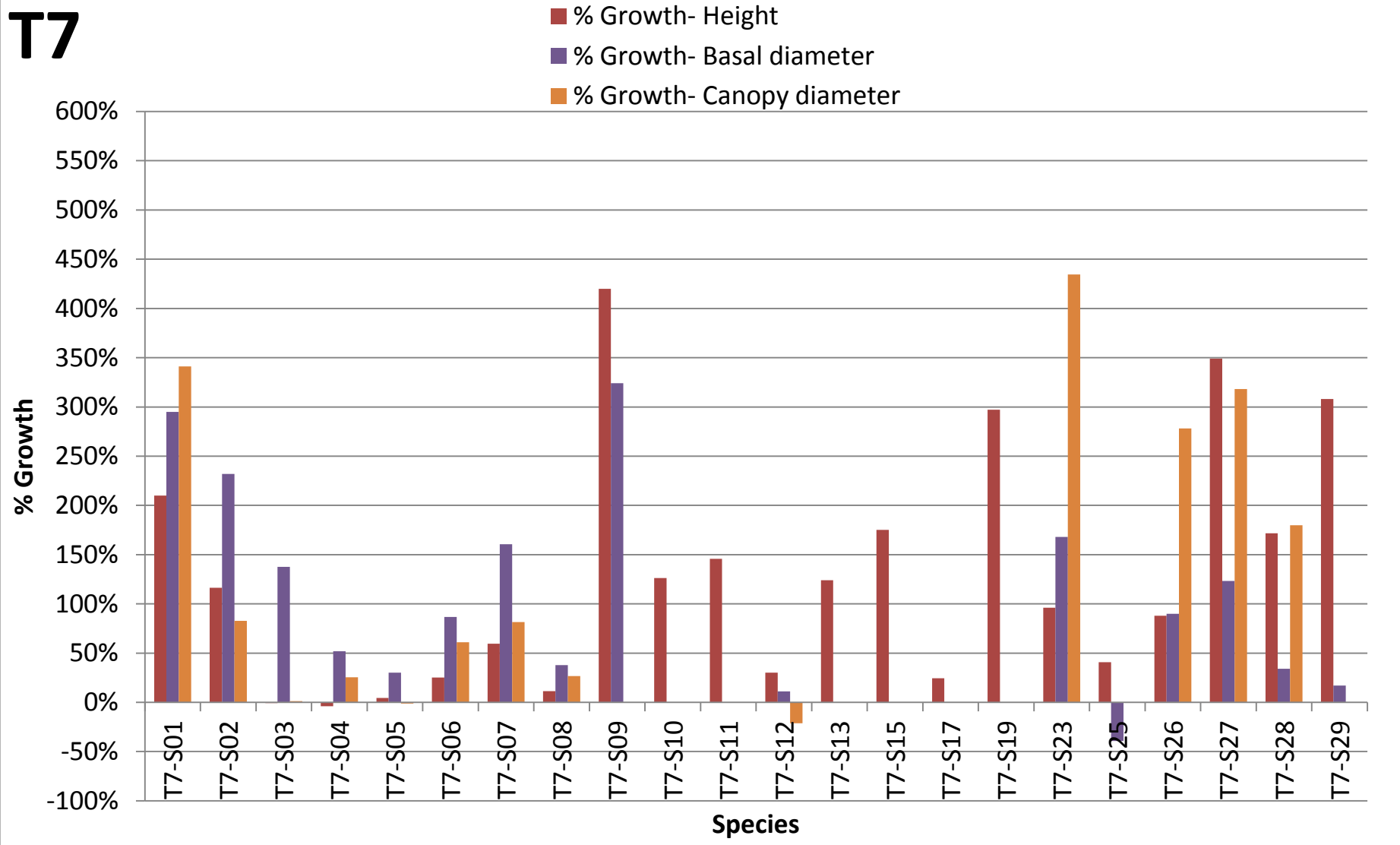


Figure 71: Graph of T7 with all species on the x-axis, indicating percentage increase in height, basal- and canopy diameter

# T8

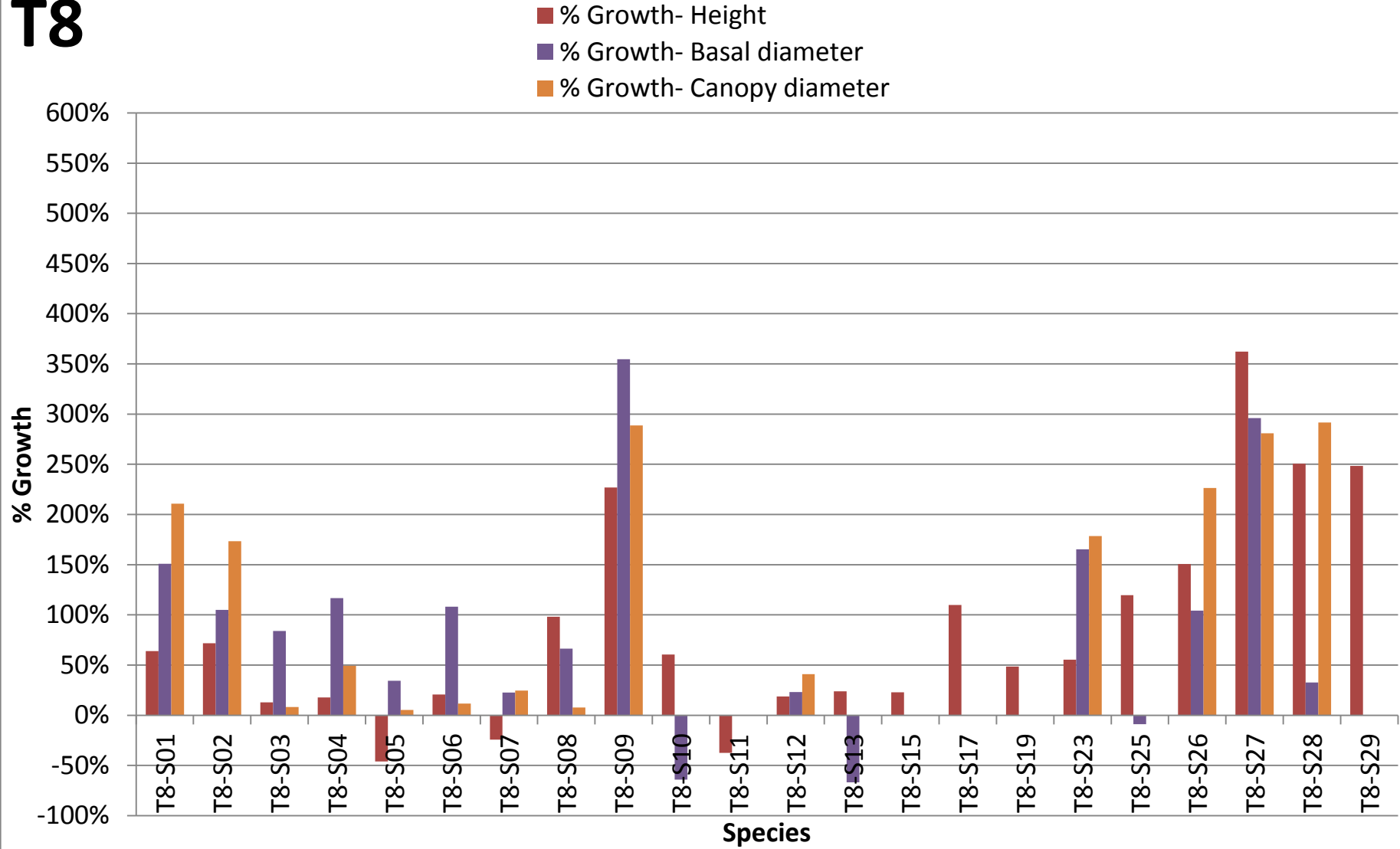


Figure 72: Graph of T8 with all species on the x-axis, indicating percentage increase in height, basal- and canopy diameter

# T9

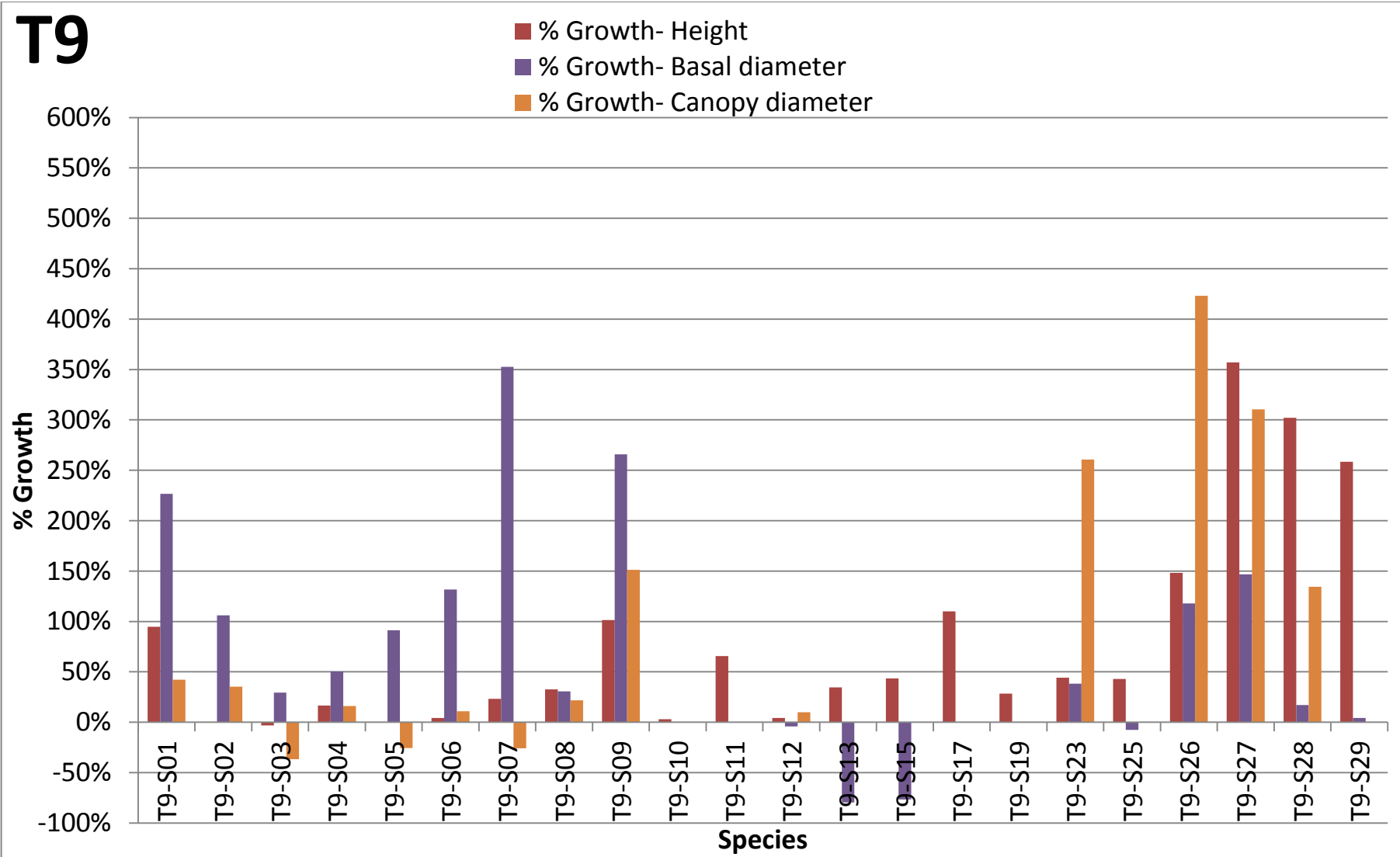


Figure 73: Graph of T9 with all species on the x-axis, indicating percentage increase in height, basal- and canopy diameter

# TC

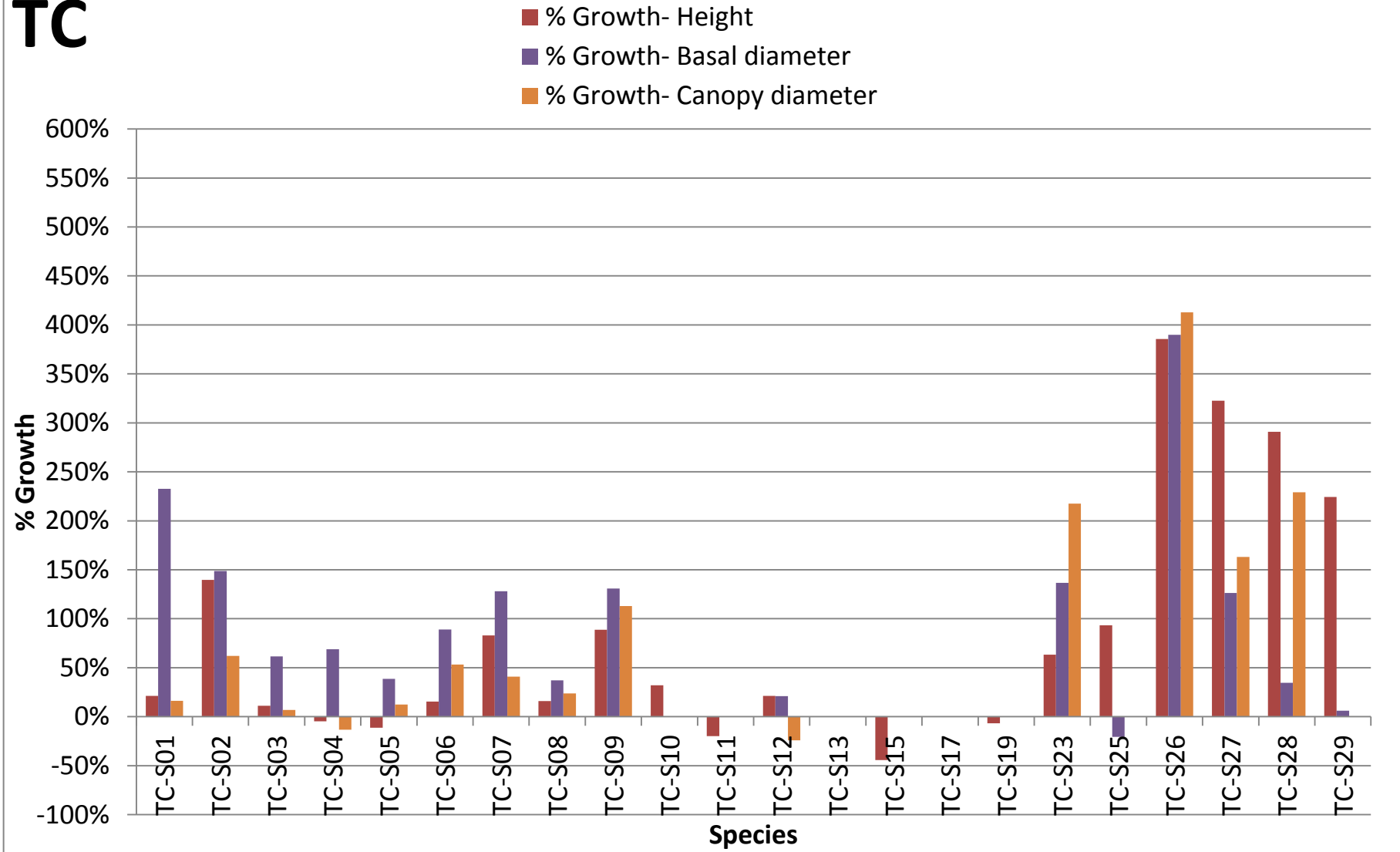


Figure 74: Graph of TC with all species on the x-axis, indicating percentage increase in height, basal- and canopy diameter