KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI

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DEPARTMENT OF THEORETICAL AND APPLIED BIOLOGY

THE EVALUATION OF THE EFFECTIVENESS OF REVEGETATION METHODS CURRENTLY USED BY ABOSSO GOLDFIELDS FOR RECLAMATION OF DEGRADED LANDS

By:

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DECLARATION

I hereby declare that this submission is my own work towards the Msc Environmental Science and that to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in text.

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ABSTRACT

The effectiveness of re-vegetation methods for lands disturbed by mining operations was investigated at Abosso Goldfield Ltd mine concession between July and August 2010.

Three categories of re-vegetated sites namely (1) decommissioned tailings storage facility (South Tailings Storage facility: STSF-L), (2) borrow area (South Tailings Storage facility Borrow Pit; STSF-Bp) and (3) waste rock dump (Tomento South Waste Rock Dump: TMS) and a secondary forest (Rex Haul road forest: RHR-F) as control site were used for the study. For each site, reconnaissance survey was conducted to select appropriate sites for the study. Sampling was conducted in 25m X 25m main plot representative of the selected sites. The main plot was sub-divided into twenty-five 5m X 5m sub-plots and 10 sub-plots were randomly selected for the study.

Flora survey for composition and abundance were conducted in the 10 selected sub-plots. Composite soil samples for depth of 0-20cm and 20-40cm were obtained, using a screw auger, for soil analysis. Earthworm extraction using the 2% formalin was done in three 30cm X 30cm quadrats laid in the 10 selected sub-plots.

The findings of the study showed that topsoil management and replacement is very vital in the recovery of disturbed lands. Of the three revegetation methods studied, the method at TMS was the most effective followed by the method at STSF-L and the least effective was the method at STSF-Bp. It was also found that the use of *Pueraria sp, Acacia mangium* and *Leucaena leucocephala* were beginning to pose invasion problems.

Based on these findings, it was recommended that: One, subsoil pulverization followed by sufficient topsoil replacement should be ensured in the revegetation of Borrow pits. Two, revegetation at STSF-Bp be reinitiated in order to meet mine closure reclamation objectives. Three, thickness of replaced topsoil should be increased to better facilitate the integrated revegetation approach and reduce maintenance cost. Four, to arrest species invasion problems, locally available species such as *Centrosema pubescens should be* used in place of *Pueraria sp* for cover material whereas for tree species, *Anacardium occidentale, Casuarina equisetifolia, Gliricidia sepium and Musanga cecropioides* be used in place of *Acacia mangium* and *Leucaena leucocephala*

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CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Expansion within the mining and metallurgical sector is central to the development and economic growth of many developing countries (World Bank, 1997). Ghana is the second largest gold producer in Africa and ranks around tenth in the world. According to World Bank figures, the mining sector now accounts for more than 30% of Ghana's gross foreign exchange earnings (Akabzaa, 2008 and World Rainforest Movement, 2008).

On the other hand, like any other economic activity, mining always has opportunity cost. Depending on the location, some form of resource has to be sacrificed to make way for mining activities. Globally, mining and other industrial activities have contributed about 10% of land degradation (Oldeman, 1994; Koranteng, 2007). According to the Ministry of Mines and Energy - Ghana, approximately 30% of Ghana's land is currently under concession to gold mining firms (World Rainforest Movement, 2008) at the expense of forests, settlements, agriculture etc. For instance, from 1990 to 1998, gold mining investment in the Wassa-West District of Ghana resulted in the displacement of 14 communities with combined populations of 30,000 (Akabzaa and Darimani, 2001).

The forests are a source of livelihood to the people and also provide ecological services such as watershed protection. However, Ghana loses 22,000 hectares of forest every year (Oldeman, 1994; Koranteng, 2007) and after decades of deforestation and forest degradation less than two percent of Ghana's native forest is left intact (World Rainforest Movement, 2004).

The negative environmental impact of mining tends to overshadow the economic sides of such projects. The International Council on Mining and Metals (ICMM) defines sustainable development as "investments that are technically appropriate, environmentally sound, financially profitable and socially responsible" (Commonwealth of Australia, 2006). Therefore, for mining activities to be sustainable, its negative impacts have to be mitigated for. To ensure sustainable land use, the National Land Policy for Ghana states that whoever takes land for mining operations should as much as possible prevent the destruction of the environment and where this is not possible, the responsible organization should ameliorate or restore same to the state it was before the operation (Republic of Ghana, 1999). It is imperative for mining companies to restore the degraded areas through various reclamation methods.

1.2 PROBLEM STATEMENT AND JUSTIFICATION

When land is surface-mined, the entire forest, including shrub layer, tree canopy, root stocks, seed pools, animals, and microorganisms, is removed. This surely affects the fertility and productivity of the soil. Revegetation programs seek to reverse these impacts but in order to achieve the mine closure objective, the rehabilitation methods have to be effective. Moreover, since rehabilitation comes at a great cost to the mining company, the methods used have to be effective to warrant the expenditure.

Within the legal framework for mining in Ghana, every mining firm undertakes soil form of rehabilitation. The question then is on how effective the methods employed are at achieving the desired objectives so as to reverse the current trend of degradation. When the methods employed are effective, damage to land resource is repaired in good time whiles affording the company economic benefits. For revegetation to be successful, it should start from the soil resource whiles looking at causes rather than symptoms. However, for most cases, because success criteria by regulatory bodies are often vegetation-biased, mining companies tend to be more elaborate on the flora and give little attention to soil and fauna. Thus, an area may be declared successfully revegetated only to fail afterwards.

This study intends to assess the effectiveness of current methods of reclamation to provide useful information in a number of areas. It is hoped that this research will provide early warning signs as well as data based on which future evaluations can be made. This research is also expected to provide information for regulatory bodies such as Minerals commission and Environmental protection Agency (EPA) to develop a more holistic composite criteria consisting of fauna, flora and soil characteristics in declaring a site successfully revegetated. It is hoped that the results of the study will help ameliorate the deterioration of the forest ecosystem.

1.3 AIM AND OBJECTIVES

Aim: to assess the effectiveness of current methods of revegetation used by Abosso Goldfields Ltd (AGL).

Objectives:

1. To identify revegetation methods and practices used by the mining company.
2. To assess and compare the floristic composition of the degraded and undegraded areas.
3. To assess and compare soil physicochemical characteristics of degraded and undegraded areas.
4. To assess the impact of soil degradation on the fauna.
5. To assess and compare revegetation methods.

1.4 SCOPE OF THE STUDY

It has been reported that most studies to evaluate revegetation success are based on the assessment and comparison of vegetation (Zhang *et al.*, 2006; Munshower, 2000).

The present study sought to look at the entire picture by determining the floristic composition, soil physicochemical characteristics and status of fauna return using earthworms as indicators. It is hoped that the data gathered will provide a fuller picture to evaluate and compare the effectiveness of revegetation methods currently used at Abosso Goldfields Ltd.

1.5 DELIMITATION

The present study used all factors including flora and fauna which could be affected by land degradation in order to evaluate the effect of mining on fertility of the land.

CHAPTER TWO

2.0 LITEREATURE REVIEW

2.1 MINING – RELATED DISTURBANCE

Mining operations may be categorized as either surface or underground. Surface mining activities are grouped as exploration, disposal of overburden and waste rock, ore processing and plant site operations, tailings containment, treatment and disposal, infrastructure, access and energy and construction of work camps and operational town sites (World Bank, 1997). All these activities exert negative impacts on the environment.

The main negative impacts of mining on the ecosystem include vegetation and soil removal as well as soil compaction resulting from trampling by heavy equipment. When topsoil is stripped and stockpiled, soil structure, seed pool, nutrient levels and biological activities are affected.

Disturbance refers to deviations from the normal or desired state of an intact ecosystem. Depending on the degree of disturbance, a disturbed area may be described as degraded, damaged or destroyed. ***Degradation*** pertains to subtle or gradual changes that reduce ecological integrity and health whereas ***damage*** refers to acute and obvious changes in an ecosystem and an ecosystem is ***destroyed*** when there is removal of all macroscopic life and commonly ruins the physical environment (Society of Ecological Restoration, 2002).

2.2 CATEGORIES OF DISTURBED SITE REPAIR

Depending on the goal and activities involved, repair of a disturbed site may be described as revegetation, rehabilitation, reclamation or Ecological restoration.

2.2.1 Revegetation

Revegetation is the growth or reintroduction and establishment of new vegetation on a previously disturbed land based on a comprehensive analysis the stressors that affect plant growth and development (Atyeo and Thackway, 2009).

2.2.2 Rehabilitation

Rehabilitation is the process of reshaping and revegetating land to restore it to a stable condition with a land-use that is appropriate for the particular location (Queensland Mining Council, 2001).

2.2.3 Reclamation

Reclamation is the process of returning the soil and the plant community it supports to conditions in which the stability and productivity of the site are comparable to that of the site prior to disturbance (Munshower, 2000).

2.2.4 Ecological restoration

Ecological restoration is an intentional activity that initiates or accelerates the recovery of an ecosystem that has been degraded, damaged or destroyed. It emphasizes process repair over structural replacement and treating the causes rather than the symptoms of degradation; monitoring protocols to allow for adaptive management (Society of Ecological Restoration, 2002).

2.3 REVEGETATION

2.3.1 Revegetation Methods

Revegetation methods refer to the site-specific alternative combinations of practices from land preparation through plant introduction and maintenance by which a disturbed area is revegetated. The nature and extent of disturbance defines the possible feasible combinations. Thus different combination of practices (revegetation methods) are required for different situations such as decommissioned tailing storage facility, haul roads, waste rock dumps, campsite etc.

The direction of revegetation depends on the legal requirements, the proposed end land use, landform, climatic conditions, pre-revegetation and soil characteristics.

2.3.2 Goal and objectives of Revegetation

The *ultimate goal of* revegetation is the return of disturbed land to a stable, productive and self-sustaining condition (Queensland Government, 1995). The goal ranges from conversion to a different kind of ecosystem or land use type to re-establishment of pre-mining conditions. According to Hossner (2000), the latter becomes necessary when: (1) critical wildlife habitat is to be mined and (2) if the existing pre-mining area exhibits a general habitat. The *objectives*, depending on the goal may include: provision of wildlife habitat especially for rare species; maintenance of biodiversity; erosion control etc.

2.3.3 Revegetation Approaches

In principle, there are three possible approaches to the revegetation of a disturbed site.

2.3.3.1 Passive or Natural Revegetation

This approach relies completely on spontaneous natural processes. It makes use of natural factors such as wind, rain, stream flow and animals as restoration agent. Although it has the advantage of introducing the local genetic stock, the disadvantage is that it is slow and is usually insufficient for adequate and rapid revegetation of disturbed sites (Hossner, 2000).

2.3.3.2 Active or Augmented Revegetation

This approach adopts technical measures exclusively. It involves direct seeding or transplanting, installing and maintaining an irrigation system, and following a weed management schedule. It has the advantage of achieving adequate and rapid results but a disadvantage of being expensive.

2.3.3.3 Integrated Revegetation

This approach combines (integrates) passive and active revegetation by directing natural succession. In this approach, human intervention seeks to orient and accelerate natural processes bearing in mind the relevant question of "where and when is an intervention really justified" (Khater and Arnaud, 2007).

2.3.4 Process of revegetation

The revegetation process is grouped under three main categories namely: (1) earthworks (2) plant introduction and (3) maintenance, monitoring and evaluation.

2.3.4.1 Earthworks

2.3.4.1.1 Removal and storage of overburden material

Overburden material or spoil refers to the soil and consolidated material layer between soil surface and mineral ore which is removed during mining. Pre-mining physicochemical assessment of total overburden strata is done to select suitable, high quality overburden materials to be removed and stockpiled for reuse so that handling cost is reduced (Hossner, 2000; Natural Resources Conservation Service, 2006). Careful management of topsoil during removal and stockpiling is essential to maintain its structural and biological properties, including the native seed bank (Queensland Government, 1995). Therefore, stockpiles are located so as to protect against wind and water erosion, dust generation, unnecessary compaction and contamination by noxious weeds, invasive species or other undesirable materials (Natural Resources Conservation Service, 2006).

2.3.4.1.2 Landform reconstruction

Landform reconstruction involves re-establishment of a stable topographic profile that provides for acceptable drainage patterns before other revegetation activities follow. If re-establishment of original native vegetation is the proposed land-use, the rehabilitated topography may need to be similar to that occurring in the surrounding undisturbed landscape (Queensland Government, 1995). On wetland sites, re-creation of water table/ground surface relationships is critical.

2.3.4.1.3 Topsoil replacement and site preparation

Newly constructed landforms require topsoil and subsoil suitable for the vegetation type. Post-mining soil analysis is carried out and compared with pre-mining soil analysis to estimate the level of stabilization need to ensure economic efficiency (Felleson, 1999). It helps to identify stressors that will inhibit the reintroduction of plant cover.

Adequate site preparation to enhance initial plant establishment and increase soil stability is one of the most important factors in determining the success of revegetation projects (Hossner, 2000). Topsoil should be spread evenly over the surface and must also be of adequate thickness. At least a four feet thick uncompacted non-toxic layer of soil at must be laid over re-contoured areas" (Burger and Zipper, 2002 and Munshower, 2000). Tillage is done to remove debris or undesirable materials that will interfere with reclamation operations (Natural Resources Conservation Service, 2006), to deal with compaction after earth moving activities, to provide optimum soil conditions to support vegetation growth, to improve water infiltration and minimize soil erosion. Common types include deep ripping, chisel plowing and disc plowing.

2.3.4.1.4 Erosion Control

Erosion control measures aim at control and management of rainfall and storm water runoff to preserve the soil resource and nutrients. During high intensity storms, runoff is the balance between rainfall influx and infiltration. Thus simple erosion control measures aim at improving infiltration rate and reduce slopes which aid runoffs. Contour furrows and/or contour banks are useful in reducing slope length and aid water infiltration. Drainage ways with sufficient capacity and stability are needed to carry concentrated runoff from the reclaimed area without causing erosion" (Natural Resources Conservation Service, 2006). The use of appropriate cover plant materials is also very useful.

2.3.4.2 Plant Introduction

2.3.4.2.1 Species selection

Suitable native or exotic species appropriate for the agreed end land use are selected for revegetation (Natural Resources Conservation Service, 2006; Atyeo and Thackway, 2009). Only seed species that will not come back naturally from the soil seed bank are selected (Alberta Environment, 2003).

Cover materials refer to fast growing grasses and legumes used to provide surface cover protection against erosion especially on gentle slopes (Alberta Environment, 2003). The problem with use of cover material is that they germinate and establish much more quickly than native species, thereby suppressing soil seed stock or competing with trees and shrub species (Burger and Zipper, 2002). This problem is solved either by growing the cover material and trees together or control of cover materials during the establishment of tree species (Queensland Government, 1995)

Tree species selection depends on the agreed post-mining land use. For example at some sites, post-mining land use requires the establishment of a native plant community or trees for conservation purposes or commercial timber production (Queensland Government, 1995). However, the species selected should be fast-growing and should not require intensive methods to establish. A range of properties have been identified which make tree species suited to soil improvement. For many purposes, tolerance to initially poor soil conditions, high biomass production, nitrogen fixation, fast-growth, not requiring intensive methods to establish and litter with high nutrient content are suitable. According to Young (2002), principal trees and shrubs that have been employed for soil improvement include *Acacia mangium, Anacardium occidentale, Azadirachta indica, Casuarina equisetifolia, Gliricidia sepium, Leucaena leucocephala, Musanga cecropioides, Senna siamea* etc.

2.3.4.2.2 Plant introduction methods

Three ways of introducing plant species are natural dispersal, direct seeding and transplanting of pre-nursed seedlings (Hossner, 2000).

Natural dispersion may be through soil seed pool, natural invasion or dispersion by animals. It is dependent on the characteristics of vegetation of undisturbed surroundings and composition of topsoil plant propagules reservoir etc. From species composition standpoint, it is a means of introducing indigenous species that are difficult to obtain but it may also introduce weedy species.

Direct seeding is used for species that reproduce sexually. Success depends upon adequate soil preparation, proper timing, methods and rates of seeding (Hossner, 2000). Methods of direct seeding include broadcasting, drilling and hydro-seeding. *Hydroseeding* technique consists on spraying a mix of water, assortment seeds, fertilizer and mulch, such as paper pulp mixed with indicator dye in a water and glue solution by means of a pump and a hose directly to steep slopes and hard-to-access areas to be restored (Khater and Arnaud, *2007).*

Transplanting of seedlings from nursery or from the wild is more expensive than direct seeding but more reliable when environmental conditions are sufficiently harsh (Hossner, 2000). Transplanting of seedlings is used for species with low or variable germination or propagated vegetatively. To ensure the required plant density is achieved, the sowing rates need to consider seed losses and seeding failure during establishment. Pre-mining vegetation survey provides a guide on possible plant density for determination of planting rate. Spacing of trees takes final tree size into consideration. For erosion control recommended planting rates for grasses and trees respectively are 300seeds/m^2 and 1000trees/acre (AGL, 2010).

2.3.4.3 Maintenance, Monitoring and Evaluation

2.3.4.3.1 Maintenance

Hossner (2000) broadly classifies maintenance activities as protective (e.g. fencing), corrective (to alleviate problems or failures e.g. replanting and weed control) and manipulative (e.g. pruning and training). Irrigation is considered if precipitation is irregular. Maintenance and repair of water management structures, including contour drains, waterways and sediment control structures, is essential. Where erosion has occurred due to inappropriate design or failure of structures, remedial action must be undertaken promptly and the area re-treated.

Fertilizer application (organic or inorganic) is done to encouraging plant growth especially for the initial establishment depending on initial soil levels. Inorganic fertilizer used may be simple/straight (containing only one element) or compound (containing two or more elements) e.g. urea, ammonium nitrate, sulphate of ammonia, superphosphate. Valuable sources of organic fertilizer includes farm yard manure, sewage (sludge and effluent) etc. For fertilizer application to be effective and economical, it has to be based on comprehensive soil analysis to determine accurate application rate. Periodic soil testing and checking of vegetation is necessary to determine if additional soil amendments are needed. Nitrogen and phosphorus are the elements most often limiting to plant growth. Accurate application rate is essential because for trace elements since very high levels tend to be toxic.

Weed control is done to assist the establishment of trees. Care has to be taken to use methods that are compatible with the survival of desirable native plants in the stand. Noxious weeds and invasive problem plants are best controlled in the early stages. Non-persistent annual weeds are only controlled if they are inhibiting the growth of desirable native plants. (Alberta Environment, 2003)

2.3.4.3.2 Monitoring and evaluation of revegetation Success

Monitoring to assess progress in achieving the objectives requires a reference for comparison. Monitoring is used to evaluate the success, improve the effectiveness of revegetation methods and evaluate the return on revegetation investment.

Performance standards or success criteria are benchmarks of the reference ecosystem based on which objectives of revegetation are evaluated to determine whether or not project objectives have been attained. The reference could be one or a combination of three possible references for re-vegetation success namely: (l) pre-mining or baseline condition (landform, soil and vegetation surveys), (2) analogues; adjacent undisturbed sites with similar conditions and floral composition - if baseline unavailable or the area had been cleared prior to mining and (3) standards set by regulatory bodies; attainment of minimum standards set forth in the mining permit application (Hossner, 2000; Munshower, 2000; Clark and Hutchinson (2003); Queensland Government, 1995 and Society of Ecological Restoration, 2002).

If interpretation of the data collected during monitoring shows that performance standards have been met, there can be no doubt that project objectives were achieved, and the restored ecosystem is likely to be sufficiently resilient to require little or no further assistance from the restoration practitioner, it can be said that the revegetation is successful. According to Alberta Environment (2003) and Society for Ecological Restoration (2004), revegetation is considered successful if (1) the revegetation goal in the reclamation plan has been met and (2) Landform stability is achieved.

2.4 CRITERIA FOR EVALUATION OF REVEGETATION SUCCESS

Holistically, there are three main categories of criteria for evaluation of revegetation success namely flora (vegetation), fauna re-colonization and soil characteristics.

2.4.1 Vegetation as Revegetation Success Criteria

Over the years, most success criteria for revegetation have always been based on vegetation production and appearance with the assumption that it is an indicator of soil health in that a plant integrates the host of soil properties in the root zone. According to Gann and Lamb (2006), with regards to vegetation, revegetation is declared successful if the vegetation:

1. can be used in the same manner and in conjunction with adjacent lands and that the productivity is equivalent or better than that of vegetation surrounding the disturbed area.
2. has sufficient numbers of the desirable species (consisting of indigenous species to the greatest practicable extent) been successfully established that provide sufficient aerial cover (live and litter) to adequately protect the site from soil erosion

3. shows secondary succession illustrated by the invasions of populations
4. shows evidence that it is self-sustaining to the same degree as its reference ecosystem and demonstrate that the existing or proposed end land use(s) can be sustained.
5. shows evidence that potential threats to the health and integrity of the restored ecosystem from the surrounding landscape have been eliminated or reduced as much as possible.

2.4.2 Soil Physicochemical Characteristics as Revegetation Success Criteria

The development and establishment of vegetation of any plant community depends on the biological and the physicochemical properties of the soil. For a fact, when soil is in good health, it can support any vegetation in the long run. However, the criterion for judging the success of reclamation has always been based on the aboveground indicators (appearance and production of vegetation) whereas the information for soil ecosystem during is often ignored (Zhang *et al.*, 2006; Munshower, 2000). Thus there is little published information on soil quality in relation to reclamation success.

Quality of soil resource should be included in success criteria (Munshower, 2000). One reason is that "soil variation is one source of biodiversity" (Koptsik *et al.*, 2001). According to Munshower (2000), since vegetation is in reality a visible reflection of the attributes of the root zone, if the surface soil horizons express certain characteristics, vegetation will develop on and in it whether intentionally seeded or not. Munshower adds that soil quality as reclamation success criteria is especially necessary because plants are very opportunistic and resilient; they can mask deficiencies of reclamation for years but will eventually fail if the soil resource is not rehabilitated sufficiently to insure the perpetuation of the plants. The presence of low cation exchange capacity and coarse textured materials should be enough to prevent declaration of reclamation success even though plant growth on the soil surface may meet all success criteria as defined by pre-reclamation agreements (Munshower, 2000).

Reclaimed plant community must, with time, be enhancing the quality and quantity of the soil resource in which it is growing. If not, natural losses will eventually contribute to the destruction of vegetation on the reclaimed site. The work of Zhang *et al.*, (2006) showed that, with age, revegetation resulted in significant increases of some soil nutrients (organic C, total N, total P and available P) and physical conditions (water holding capacity and porosity), but insignificant decrease of bulk density.

The quality of topsoil can be defined by determination of the chemical, physical, and biological characteristics of the material. Measurement of major soil characteristics can serve to indicate that the disturbed soil has or is in the process of recovering from disturbance. Parameters of major importance to a healthy soil system to be measured include infiltration rate and water holding capacity, cation exchange capacity, organic matter content, and concentrations of the major and minor nutrients (Munshower, 2000).

2.4.2.1 PHYSICAL PROPERTIES

2.4.2.1.1 Soil texture

Texture affects practically all of the factors governing plant growth and so different plants require different textural class for establishment and optimum growth. Soil texture influences the water-holding capacity and drainage, aeration, nutrient holding capacity and supply, structure, resistance to compaction, resistance to changes in acidity and resistance of the soil to root penetration (FAO, 2000; Brady and Weill, 1996). In terms of nutrient holding capacity and supply, very sandy soil hold little, very silty soils are medium and very clayey soils are very high; organic matter decomposition is rapid in very sandy soils, medium in very silty soils and slow in very clayey soils and for resistance to compaction, very sandy soil are good if coarse, very silty soils and very clayey soils are both easily compacted (Brady and Weill, 1996).

2.4.2.1.2 Bulk density and Porosity

Most rocks, as a rule of thumb, have a bulk density of 2.65 g/cm^3. Thus, ideally, a medium textured soil with about 50 percent pore space will have a bulk density of 1.33 g/cm^3. For most soils bulk density ranges from 1- 2 g/cm^3 (Houston *et al., 2002).*

The bulk density and porosity of a soil are used to give most useful indication of the degree of soil compaction. Sandy soils with low porosity have greater density (1.2 to 1.8 g/cm^3) than clay soils (1.0 to 1.6 g/cm^3) which have a greater volume of pore space. Compaction can raise the density of the surface horizons to values that may reach 2 g/cm^3 (FAO, 2000).

Bulk density is affected by organic matter content, soil structure and porosity (Houston *et al., 2002).* Generally, loose, porous soils and those rich in organic matter have lower bulk density. Bulk density typically increases with soil depth since sub-surface layers are subject to the compacting weight of the soil above them, have low porosity (from less pore space) and reduced organic matter (Houston *et al.,* 2002). The soil fauna, especially earthworms, create vertical macropores of various sizes in undisturbed soil, increasing aeration, infiltration rate and permeability (FAO, 2000).

2.4.2.1.3 Hydraulic Conductivity

Hydraulic conductivity depends on porosity, the configuration of the soil pores. It is affected by soil texture (sandy soils generally have higher saturated hydraulic conductivities that fine textured soils) (Brady and Weill, 1996). Hydraulic conductivity is also related to soil bulk density (FAO, 2000). For example, at bulk densities ranging from 1.6 to 1.7g/cm^3, water movement is hindered at this point down the profile (USDA, 2008).

2.4.2.2 CHEMICAL PROPERTIES

2.4.2.2.1 Soil Reaction (PH)

Soil pH is critical to the availability of all nutrients one way or another (Ryan *et al.*, 2001). It influences solubility of toxic nutrients, physical breakdown of root cells, CEC in soils whose colloids are pH-dependent and biological activity. Acidic pH is associated with a lower cation exchange capacity and base saturation percentage, a high proportion of exchangeable aluminium, reduced solubility of phosphorus and reduced activity of many soil organisms (Rowell, 1994). Koptsik *et al.,* 2001 found that pH and organic matter are the best soil related predictors of species diversity parameters.

According to Sheoran *et al.,* (2010) a pH of 5.5-7.0 provides most satisfactory soil nutrient levels generally and hence optimal vegetation growth. When the soil pH drops below 5.5, reduced legume and forage growth occur due to metal toxicities such as aluminum or manganese, phosphorus fixation, and reduced population of N-fixing bacteria (Sheoran *et al.*, 2010). In extreme cases it results in an accumulation of organic matter, reduced mineralization and low availability of nitrogen, phosphorus and sulphur.

2.4.2.2.2 Cation Exchange Capacity, Total exchangeable base, Base Saturation and Exchangeable acidity

CEC relates to the ability of a soil to retain nutrients and prevent nutrient leaching. CEC above 50 is high, and such soils should be able to hold ample nutrients. Soils with a low CEC can only hold a small quantity of nutrients on the exchange sites so that the excess nutrients applied to the soil can easily be leached out by excess rain (FAO, 2000). CEC is affected by clay, organic matter contents and soil pH (CEC of most soils increase with increasing soil pH). Coarse soils have inadequate number of exchange sites to prevent leaching of nutrients; sandy soils may have CEC < 10 while clays and highly organic soils have high CECs (Munshower, 2000; FAO, 2000; Brady and Weill, 1996).

Percentage base saturation indicates the tendency towards neutrality and alkalinity and is inversely related to acidity whiles exchangeable acidity indicates the tendency towards acidity.

2.4.2.2.3 Total Nitrogen, Soil Organic Matter (SOM) and Total organic carbon (TOC)

Of all the components of soil, organic matter is the most important because it influences chemical, physical and biological properties of the soil as well as acts like a bank for many essential plant nutrients and provides exchange sites for cations (Ryan *et al.,* 2001). Organic matter is the major source of nutrients such as nitrogen, and available P and K in unfertilized soils (Donahue *et al*., 1990). It also increases the water holding capacity as it can absorb water to a ratio of three to five times its own weight, which is very important in the case of sandy soils (FAO, 2000).

Organic carbon is positively correlated with available N and K and negatively correlated with Fe, Mn, Cu, and Zn (Maiti and Ghose, 2005). A level of organic carbon greater than 0.75% indicates good fertility (Ghosh *et al*., 1983).

Soil Nitrogen is considered the most important determinant of plant growth but often limiting and tends to decrease with depth (Ryan *et al*., 2001). The nitrogen status is closely associated with the soil organic matter content. According to Brady and Weill, (1996), the organic matter to nitrogen ratio of 20:1 is constant. Good Soil Organic Carbon (SOC) level leads to increased biological activity by serving as the main source of food for detritus feeders who in turn serve as food source for a complex food web.

2.4.2.2.4 Carbon to Nitrogen (C:N) ratio

The C:N ratio is important in controlling the available nitrogen, total organic matter and rates of decay. It gives an indication of level of biological activities especially organic matter decay in a soil. When organic residue (with high C:N ratio) is incorporated into a soil, the larger organisms like mites first break it into smaller pieces through their feeding activities. Heterotrophic flora - bacteria, fungi and actinomycetes continue the degradation until a ratio of 10:1 - 12:1 is reached (Brady and Weill, 1996; FAO, 2000). C:N ratio of the upper 15cm of arable soils commonly range from 8:1 to 15:1 with a median of 10: 1 - 12: 1. It is lower for warmer regions and for subsoils (Brady and Weill, 1996). C:N ratio of greater than 20 means organic matter decomposition is active but in situations of low pH, it could mean accumulation of organic matter.

2.4.2.2.5 Potassium

Along with nitrogen and phosphorus, potassium is also of vital importance in plant growth. Although potassium appears to be readily available in most tropical soils, the levels are often low. Most soils contain relatively large amounts of total K (1-2%) as components of relatively insoluble minerals, however, only a small fraction (about 1%) is present in a form available to plants. Highly weathered tropical acid soils are more frequently deficient in plant available K because leaching losses can be severe.

2.4.2.2.6 Phosphorus

Phosphorus (P) is an essential element for all plants. It is deficient in most soils and the average level in surface soils is 80-150ppm (Watson and Mullen, 2007). The problem of phosphorus in soil fertility is three-fold: One, mineralization of readily available organic P to inorganic solution P occurs in most soils but it is usually too slow to provide enough P for crop growth. Two, inorganic phosphorus easily gets fixed because P is negatively charged in most soils and reacts readily with positively charged iron (Fe), aluminum (Al), and calcium (Ca) ions to form relatively insoluble substances. Three, phosphorus has low mobility in the soil. Factors affect available P includes nature of parent material, depth and soil pH. Soil pH is the main property controlling inorganic P forms; P availability is greatest at soil pH between 6 and 7 (Ryan *et al*., 2001).

2.4.3 Soil Fauna Indicators As Revegetation Success Criteria

Assessing the actual and predicting the future performance of ecosystems that are or may be influenced by human activities is essential to ensure a sustainable development. Establishing the state of soil biodiversity requires the use of reliable indicators that can capture the trends in biodiversity and ecosystem services. Indicators are a way of presenting and managing complex information in a simple and clear manner (European Commission, 2010).

Essentially, ecological indicators have two main functions: an informative function, i.e. to decrease the number of measures and parameters that would normally be required to represent a complex situation (e.g. an agro system), and a decision-aid function, to simplify the communication process through which information is conveyed to final users and to help achieve the initial objectives (European Commission, 2010). Many indicators relating to some aspect of biodiversity exist but none of them capture biodiversity in its entirety.

Selection of indicator organisms is based on their significance, existence and acceptance of the methodology, measurability and costs (European Commission, 2010). A number of methods exist for measurement of the biodiversity of soil organisms. Some methods directly count the number of species and individuals present in a sample to calculate diversity, whiles others are based on a community approach, and rather estimate the activity of soil organisms, or of specific functional groups (European Commission, 2010).

Among soil ecosystem engineers, earthworms are the most frequently used indicator species because they can be very abundant, not very diverse and easy to characterize and count. Also they are important for soil structure, are the main food source for many above-ground conspicuous species. They readily colonize new areas and are relatively tolerant of disturbance (Wild, 1988). Moreover, earthworms are sensitive to soil type and secondarily to land use and their abundance reflects an integration of a range of biological processes occurring in soils (European Commission, 2010).

Earthworms belong to the order Oligochaeta. Earthworms ingest organic matter and soil, subject them to digestive enzymes and egest as earthworm casts which are evidence of extensive earthworm activity. Earthworms significantly impact both soil and growing plants (Brady, 1996). Earthworms improve soils by creating vertical macropores of various sizes in undisturbed soil, increasing aeration, infiltration rate and permeability. They produce glue-like substances, including polysaccharides that help stabilize the soil structure (FAO, 2000). Earthworms are known to affect plant growth through five main mechanisms (Wild, 1988; Brady, 1996) namely: enhancement of soil organic matter mineralization; production of plant growth regulators; control of pests and parasites; stimulation of symbionts, and the modifications of soil porosity and aggregation.

Earthworms need organic matter as food source; the level of nitrogen is an important factor in controlling the size of earthworm population (Wild, 1988). They prefer medium-textured and well-drained soils and well-aerated but moist habitats. A few species are tolerant of low pH but most earthworms thrive best in soils not too acidic (Brady, 1996).

Earthworms help to alleviate pollution through their feeding activities. They feed on materials from the soil surface and thereby ingest pollutants reaching the soil, accumulate in their fat deposits and pass it on to their predators. Earthworms are less sensitive to pollutants because accumulation in fat deposits immobilizes the pollutants. For example, earthworms were found to accumulate tetrachloro dibenzodioxin (TCDD) by about 41- fold the mean soil level (Wild, 1988). Earthworms do not in general accumulate heavy metal residues although there is evidence that cadmium is accumulated to some extent (Wild, 1988).

2.5 REVEGETATION IN AGL

Revegetation in AGL is conducted within the framework of a reclamation security agreement signed with EPA - Ghana. Environmental management at AGL is conducted within the framework of an ISO 14001 certified Environmental Management System (EMS). Certification was in July 2003 and re-certification was in July 2009. The EMS is comprehensive in describing how environmental aspects of the mine will be managed.

Relevant component document in the EMS (AGL, 2010) by way of Standard Operating Procedures (SOPs) related to rehabilitation include: Proc EN 02 (procedure for rehabilitation and closure); Proc MN 06 (procedure for waste rock management); Proc SW 14 (procedure for land clearing and disturbance); Proc SW 15 (procedure for topsoil management) and Proc EN 03 (procedure for erosion control). Proc EN 02 defines rehabilitation/reclamation as the process of restoring any disturbed or damaged lands towards a defined beneficial land use and re-vegetation as the process of establishing vegetative cover on previously disturbed (and frequently re-shaped) lands.

2.5.1 Desired Result for Rehabilitation at AGL

1. To establish an ecosystem that can support the return of flora and fauna

2. To leave restorable areas in conditions at final completion that is suitable for resumption of traditional land use patterns and for establishment of agriculturally sustainable development projects.

2.5.2 Land Clearing and Disturbance

Disturbance occurs through vegetation clearing, dumping of waste, excavation of clay materials for tailings storage facility construction (borrow pits), changes to surface drainage etc. Land clearing is undertaken only when necessary for operations and this is restricted to the minimum area practicable (AGL, 2010).

Prior to any disturbances, the responsible department applies for permit through protocols such as Mining Manager and Environmental Manager (AGL, 2010). To reduce impact and reclamation cost, where secondary or tertiary forest is to be disturbed, economic trees are recovered first. Also no clearing is done more than 12 months prior to the proposed activity. Any land clearing activity is done under the supervision of a supervisor from the responsible department and a representative from Environment department to ensure that disturbances are limited to only what is necessary (AGL, 2010). It has been reported that the total disturbed area in 2009 and the gross disturbed area at the end of 2009 respectively were 27.51ha and 1096.36ha (AGL, 2009).

2.5.3 Topsoil Management (AGL, 2010)

Owing to the fact that the use of native topsoil allows succession process to be accelerated by providing seed pool and also as an excellent rooting medium, topsoil recovery and management is a key component of rehabilitation programs at AGL.

Vegetation stripping is done in a way so as to avoid mixing topsoil with striped vegetation. The maximum amount of topsoil (and sometimes suitable subsoil) available is then characterized, stripped and hauled to topsoil stockpiles. To preserved soil structure vegetation clearing and topsoil stripping and haulage is done only when soil is sufficiently dry. Heavy equipment are not allowed travel over topsoil being stockpiled to avoid compaction. To prevent multiple handling with its associated effect on soil quality and quantity, recovered topsoil may be immediately spread on areas being prepared for re-vegetation. Stockpiles are constructed in such a way as to minimize the potential for erosion by storm water and stockpile height is not allowed to exceed two meters. To control erosion and maintain nutrient and biological cycles within the topsoil, cover vegetation is established immediately after stockpiling.

Volume of stockpile is estimated and Environmental Department keeps record on them. It has been reported that by the end of 2009, total topsoil stockpile volume was 243500 m^3 (AGL, 2009).

2.5.4 Waste Rock Management (AGL, 2010)

Waste rocks, ore rocks and oxide material excavated from barren or below cut-of grade zones during mining operations, are piled into Waste Rock Dumps. Waste Rock Dumps are designed and constructed in away so as to facilitate successful rehabilitation, erosion and sediment controls, long term stability and water quality protection at minimum cost. Waste dumps are constructed in height of 15m or less. If height is more than 15m, each 15m height is separated by inter-height bench (berms) of 5-10 m width. Slopes are battered to 20-22°. Dump drainage channels and sediment controls are provided to minimize storm water flow from dump into surrounding areas.

2.5.5 Earthworks (AGL, 2010)

Earthworks required for rehabilitation include the following:

1. *Re-sloping and re-shaping:* waste dumps are re-sloped to 20-22° whiles borrow areas, pits and tailings areas are-re-shaped
2. *Dumping and spreading of oxide materials:* oxide materials that is non-economical for mining is used for capping waste dump. Oxide materials are placed up to 0.5-1m depth or to a thickness according to end-use plan. Capping of waste dump is done during the dry season to reduce compaction
3. *Deep ripping:* is done on oxide floors and compacted oxide to ease root development of the final vegetation cover. All flat surfaces which have compacted either naturally or due to traffic are deep-ripped prior to re-vegetation. Deep ripping is also done to capture seeds moved by overland flow.
4. *Topsoil re-handling, placement and spreading:* topsoil is spread on all flat surfaces and slopes of fill areas, waste rock dumps oxide cap, to a thickness of 10cm or more depending on availability and requirement
5. *Installation of drainage channels:* using windrow, v-drains and stone pitches to prevent storm water flow down the rehabilitate areas to cause erosion.

2.5.6 Erosion Control

Erosion control makes use of measures such as cover material (*Pueraria* (Plate 1) and grasses such as Vetiver grass (Plate 2), Guinea grass, *Brachiaria*, *Citronella* and Buffalo grass), construction of stone pitches (using concrete and waste rock), cutting of crest drains and rip lines across slopes, use of sand bags to trap sediments in emerging rills and gullies.

Depending on susceptibility of topsoil material and severity of erosion, combination of measures is used. For example, it has been reported that the Tomento project produced only oxide and transitional materials which, due to the weathered nature, was highly susceptible to erosion (AGL, 2004). The use of this weathered oxide materials for rehabilitation of TMS led to development of large and deep gullies that demanded re-fixing in 2008 (AGL, 2009). Waste rock was used to fill the gullies followed by battering, capping with suitable oxide (Plate 3) materials, topsoil spreading (Plate 3) and re-planting with selected vegetation (AGL, 2009). To prevent recurrence of erosion, crest drains, stone pitches (at vantage locations to channels surface water) and sand bags were employed in addition to cover crop planting (a combination of *Pueraria* and buffalo grass) (AGL, 2009).

PLATE 1: Cover material: *Pueraria sp.*

PLATE 2: AGL Vetiver grass farm

PLATE 3: Topsoil layer above oxide capping (TMS)

2.5.7 Vegetation Establishment

2.5.7.1 Plant seedling nursery

Seedling of desired tree species and economic tree species recovered from forests prior to disturbance are raised for re-vegetation purposes. It has been reported that in 2009, 16210 seedlings were raised for re-vegetation (AGL, 2009).

2.5.7.2 Tree plantations

Depending on the end-land use, appropriate plant species are planted during the rainy season. Timer species planted include: Teak, *Ceiba*, *Cedrella*, *Terminalia*, *Nauclea*, *Triplochiton*, *Milicia* etc whiles Legume species include: *Acasia*, *Senna*, *Leuceana*, *Gliricidia* etc. For example, Lima North Dumps on both sides of the Rex Haul road was in 2006 planted with indigenous timber species in resemblance of the adjoining forests (AGL, 2009). In 2009, it was reported that leguminous trees and timber species planted amounted to 3,357 and 5,116 respectively, were planted at Bus stop Dump, Victoria Waste Dump, Rex Waste Dump and Tomento Waste Dumps (AGL, 2009).

To plant selected species, pegging out is done based on the desired plant density and holes dug for planting of seedlings from the AGL Nursery (Plate 4). Where topsoil spreading was not feasible, excavated holes are filled with sufficient topsoil or compost before planting (AGL, 2010).

Total area of initiated rehab works in 2009 only and total active revegetation by the end of 2009 were 34.52ha and 389.75ha respectively (AGL, 2009).

PLATE 4: AGL Nursery

2.5.7.3 Oil palm plantations

Some areas are planted with oil palm. Seedlings are obtained from the seedling raisers in the local community. Oil palm farms have been successfully established at North East Waste Dump (NEWD), South West Waste Dump (SWWD), South Tailings Storage Facility (STSF) and Huni Farms. It has been reported that in 2009, total harvest from these four sites amounted to 79.60 tonnes (AGL, 2009).

2.5.7.4 Trial plots

Field trials are conducted with the aim of testing the suitability of the rehabilitated tailings surface for food and cash crop. The trial plot at STFS covers 3ha of STFS. Plants include coconut, cocoa, citrus, yam, maize and vegetables. Yam and maize were included owing to suggestions by local communities at public consultations meetings. It has been reported that harvests from the vegetable farms in 2009 were: cabbage (500kg); hot pepper (200kg); water melon (300kg), cucumber (100kg) and garden egg (200kg) (AGL, 2009).

2.5.8 Maintenance

Parameters measured for monitoring to assess progress of re-vegetation includes height, diameter from Girth at Breast Height (GBH) and stocking density.

Tending is the general term for re-vegetation maintenance practices in Proc EN 02 (AGL, 2010). It is done to achieve productivity and enhance rehabilitation towards progression to final ecosystem.

According to Proc EN 02, practices carried out include: general weeding, prompt repair of areas showing signs of erosion and erosion control structures, de-silting of drains, re-planting and replacement, Pest and disease control (on crop farms), mulching (AGL, 2010). Other practices described in Proc EN 02 (AGL, 2010) include:

1. *Scalping* - 0.5m radius ring weeding done after 3 months of planting and thereafter, 2 times every quarter for the first 18 months. This practice promotes growth of planted trees whiles encourages passive revegetation.
2. *Pruning*- removal of excess, dried and/ or withered off branches, twigs or stems to stimulate new shoot growth. It also reduces shade on crops and for large trees, to harvest branches for fuel wood, mulch and fodder.
3. *Pollarding* - broad removal of the entire disturbance while the main trunk is left standing. It is done 2-3m from the ground. It is done to stimulate the growth of few shoot from the stems for a new crown.
4. *Coppicing* - cutting back of the trees to 50cm or so from the ground to encourage re-growth of new shoots.
5. *Fertilizer application* - application of NPK (15:15:15) by ring placement or broadcasting at a rate of 2 bags/ha for the first 3months. After 3 months, it is done selectively on only timber species on all trees on quarterly basis for first 2years.

2.5.9 Evaluation of Rehabilitated Areas

Assessment of rehabilitation programs against standards established in Reclamation Security and Agreement are conducted and reported to EPA regularly. The assessment includes photographic demonstration of work progress over time as well on-site assessment of soil quality and crop quality and achievement of objectives and targets set in reclamation plan.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 STUDY AREA

Abosso Goldfields Ltd (AGL) is a Ghanaian registered open pit gold mining company currently owned by Goldfield Ghana Ltd (71%), IAMGOLD (18.8%) and Government of Ghana (10%). It has a total concession area of the 52.39km2 (8111 ha). It is located at about 1.5km North-east of the Damang village and 45km North-East of Tarkwa in the Prestea Huni-Valley District of Western Region of Ghana (Plate 5). It lies on latitude 5°'15'05"N and longitude 1°59'17"W.

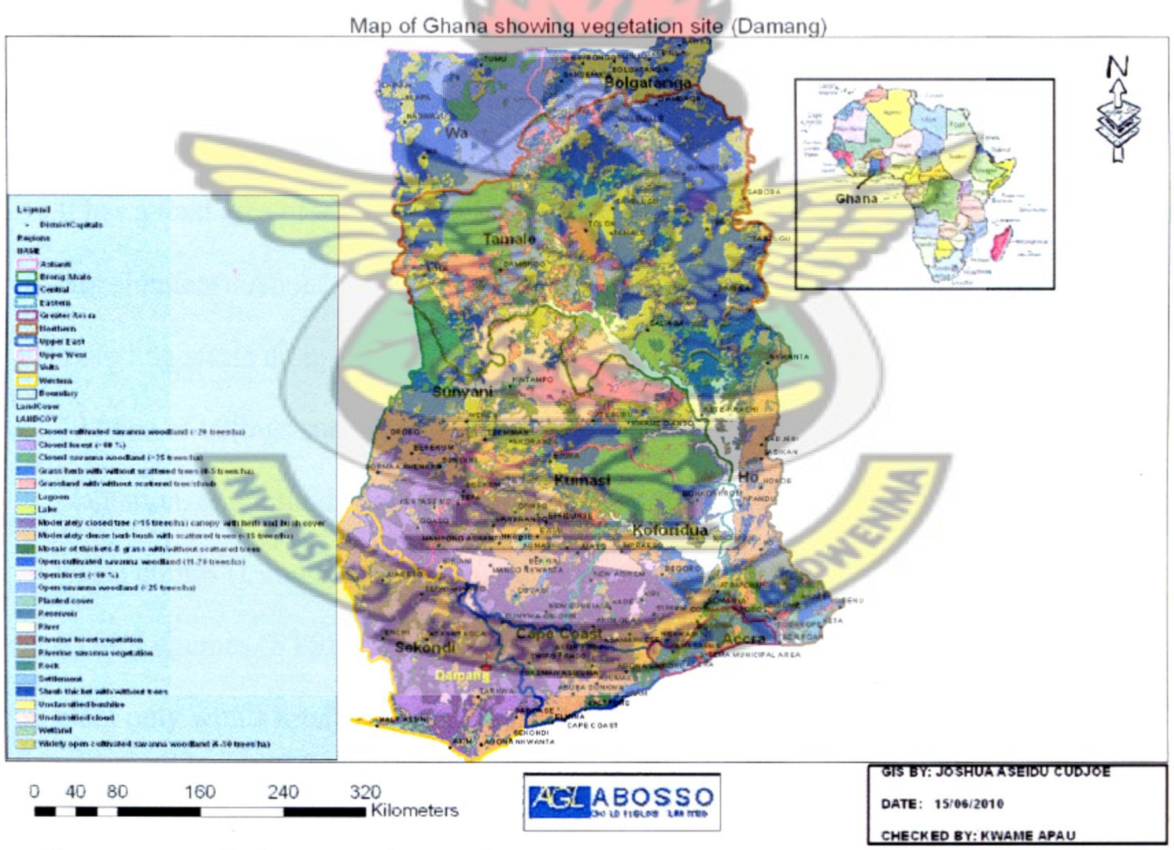


PLATE 5: Map of Ghana showing study area (Damang)

3.1.1 Brief History of AGL

The Damang Gold deposit was first discovered in 1990 by Paul Woolrich and mining operations commenced in 1997. The mine was granted Mining Leases ML 1409/96 in April 1995 and ML316/2006in April 2006 by the Minerals Commission. The mine was sold to Goldfields Ghana Ltd in February 2002.

AGL has been assessed and is operated in accordance with Ghanaian Environmental requirements administered by the Environmental Protection Agency (EPA), holds the required environmental permits and certificate. The company is also the first mining company in Ghana to sign a Reclamation Security Agreement with EPA-Ghana in May 2001 (AGL, 2009). The mine is also has ISO 14001-2004E certification and recertification was achieved in July, 2009.

AGL is noted as an environmentally committed mining company; it received the Ghana EPA awards for the Most Environmentally Committed Company – Mining Sector for the years 2004, 2005 and 2006 awarded at the World Environment Day in June 2005, 2006 and 2007 respectively. As at the end of December 2009, it is reported that, of the 52.39km^2 (8111 ha) concession area, 1096.3 (13.5%) ha has been disturbed by the mining operations and active rehabilitation works now cover 353.43ha (32.2% of disturbed lands) of the active areas (AGL, 2009).

3.1.2 Climate

The Damang mine falls within the wet semi-equatorial climate zone of Ghana. The climate is tropical; with a double maxima rainfall pattern namely major season (March to August; characterized by heavy rains) and minor season (September to November; characterized by frequent showers). The Tarkwa-Damang area has an average annual rainfall of 1600-2000mm. The Dry season runs from December to February. Average daily temperature ranges from 24.5°-28.5°C (AGL, 2009).

3.1.3 Vegetation

The vegetation of Damang is tropical evergreen forest type and falls within the rain forest belt of south-western Ghana. The three layered forest characterize the area. Due to human activities such as extensive subsistence farming, mining (both artisanal and commercial) and lumbering, the areas near the mining area are composed of secondary forests at various stages of development.

3.1.4 Background of study sites

Broadly, the two major areas used for the study were South Tailings Storage Facility (STSF: subdivided into STSF-L and STSF-Bp) and Tomento South Waste Rock Dump (TMS).

3.1.4.1 General History of South Tailings Storage Facility (STSF)

STSF was removed from active use (tailings storage) at the end of first quarter of 2002. According to AGL (2009), STSF has a total area of 72.09ha (including haul road, borrow areas, spillways and embankment). About 25ha was used in the development of the Kwesi/Lima pits including waste dumps (Lima North and south waste dumps) and haul roads. A total of 49.96 ha of tailings surface and its embankment have been rehabilitated into oil palm plantation, leguminous trees and timber and approximately 3ha for trial plots. STFS waste dumps (Lima North and South) approximately 12.58ha in size (AGL, 2009).

3.1.4.1.1 STSF-Legumes (STSF-L)

3.1.4.1.1.1 History

STSF Legumes (STSF-L) is a portion of STSF that was rehabilitated with leguminous plant only with a total size of 4.37ha and rehabilitated in 2002 (AGL, 2009).

3.1.4.1.1.2 Specific method used for re-vegetating STFS-L

In line with AGL (2010) a 1m embankment freeboard and an overflow spillway were constructed in preparation for revegetation. To establish vegetation, small pockets of holes were randomly dug in the decommissioned tailings storage facility. The holes were each filled with either a mixture of compost and seeds of *Pueraria sp.* Holes of about 0.5m deep and 0.3m wide were dug and filled with topsoil. Pre-nursed seedlings of selected plant species (the legumes: *Leucaena leucocephala*, *Acacia mangium* and *Senna* ***siamia*** were then planted the holes filled with topsoil. Application of NPK (15:15:15) by broadcasting at 2 bags/ha was once every 3months after planting for the first 2 years. ***Scalping*** (ring weeding) was done after 3 months of planting and thereafter, 2 times every quarter for the first 18 months.

3.1.4.1.2 STSF Borrow pit (STSF -Bp)

3.1.4.1.2.1 History

STSF Borrow pit (STSF -Bp) is an area just outside the tailings STSF where good grade materials were excavated (hence the term 'borrow' pit) for use in the construction of the tailings storage facility. It has a size of 0.9ha and was planted mainly with timber species and was rehabilitated in 2002 (AGL, 2009).

3.1.4.1.2.2 Specific method used for re-vegetating STFS-BP

Following the guidelines in Proc. EN. 02 (AGL, 2010), holes of about 0.5m deep and 0.3m wide were dug and filled with topsoil. In these holes pre-nursed seedlings of selected plant species (*Acacia mangium and the timber species*: *Cedrella odorata*, *Ceiba pentandra and Alstonia boonei*) were planted. Application of NPK (15:15:15) by ring placement at 2 bags/ha was done first 3months on all trees but after 3 months, it is done selectively on only timber species. *Scalping* (ring weeding) was done after 3 months of planting and thereafter, 2 times every quarter for the first 18 months.

3.1.4.2 Tomento South Waste Rock Dump (TMS)

3.1.4.2.1 History

TMS is a site where waste rocks from the Tomenta pits mine-and-haul project were piled and rehabilitated. It has a total size of 25.55ha out of which 12.05ha has been reported as rehabilitated at the time of this study. The site selected for the study was rehabilitated in 2006 (AGL, 2009).

3.1.4.2.2 Specific method used for re-vegetating TMS

Following the guidelines in Proc. EN. 02 (AGL, 2010), after waste rock dump has reached approved level, re-shaping and re-sloping was done by means of a dozer to achieve a 20-22^{o} slope. Sufficient topsoil from stockpile was spread on top of the re-shaped dump to a thickness of about 1m. Crest drains and rip lines were constructed for erosion control and *Pueraria sp.* was broadcasted on the topsoil. Planting of pre-nursed seedlings of selected plants (*Leucaena leucocephala, Acacia mangium, Senna siamia, Ceiba pentandra,* and *Tectona grandis*) were planted immediately after the *Pueraria* was broadcasted. Application of NPK (15:15:15) by ring placement at 2 bags/ha was done first 3months on all trees but after 3 months, it was done selectively on only timber species. Scalping (ring weeding) was done after 3 months of planting and thereafter, 2 times every quarter for the first 18 months.

Use of oxide and transitional materials which, due to the weathered nature, is highly susceptible to erosion, led to development of large and deep gullies that demanded re-fixing 2008 (AGL, 2009). Erosion control was by filling gullies with waste rock and to prevent recurrence, recurrence of erosion, crest drains, stone pitches (at vantage locations to channels surface water) and sand bags were employed in addition to cover crop planting (a combination of *Pueraria* and buffalo grass).

3.2 REVIEW OF CORPORATE DOCUMENTS

Documents in respect to the Environmental Management System (EMS) relating to reclamation and relevant Environmental Impact Assessment (EIA) baseline data were reviewed.

3.3 FIELD SURVEY

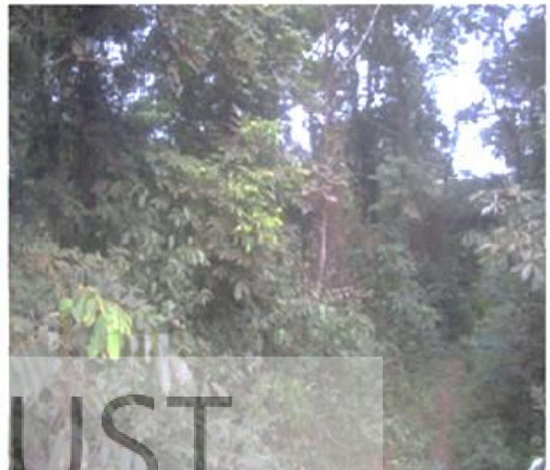
3.3.1 Reconnaissance survey

A Reconnaissance survey was carried out by walking through the various rehabilitated areas with the help of the Revegetation Officer and a plant taxonomist. This was to identify the various re-vegetation types in the study area.

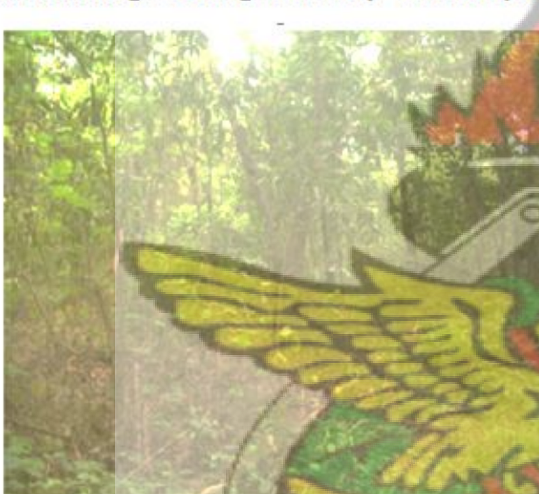
3.3.2 Selection of the sampling sites

Three sites (one for each category of re-vegetation) were selected for the study namely: (1) a re-vegetated decommissioned Tailings Storage Facility (South Tailings Storage Facility - Leguminous tree stands; STSF-L), (2) rehabilitated Borrow Pit at STSF (South Tailings Storage Facility - Borrow pit; STSF-Bp) and (3) rehabilitated Rock Waste Dump (Tomento South Waste Dump; TMS). An undisturbed forest on the Rex Haul Road (RHR-F) was used as control (Plate 6).

STSF-Bp
(South Tailings Storage Facility - Borow pit)



RHR-F
(Rex Haul Road Forest)



STSF-L
(South Tailings Storage Facility - Legumes)

TMS
(Tomento South Waste Rock Dump)

PLATE 6: Study sites

3.3.3 Sampling Plot Demarcation

For each selected site, an area of 25m x 25m was demarcated with the help of field compass and linear tape (for taking distance from the ground) and the edges marked with pegs, beacons, garden line and ribbons. This was further divided into 5m x 5m smaller plots (Plate 7). Ten quadrats were then randomly distributed and the floristic composition of the plants was assessed. GPS Coordinates were taken for the four corners of the main plot and in each of the ten subplots as shown in appendix I.

PLATE 7: Plot demarcation and sampling

3.3.4 Flora Survey

In each 5m x 5m sub-plot, rooted tree species were identified, counted and recorded to determine the densities of trees and shrubs. The floristic composition of the herb layer was assessed in 1m x 1m quadrats randomly distributed in the plots. The identification was done in-situ with the help of a plant taxonomist from Forestry Research Institute of Ghana (FORIG). Families, species and authors were identified using guide by Hawthorne and Jongkind (2006).

3.3.4.1 Determination of relative abundance of plant species

The frequency method of vegetation analysis was used to quantify the abundance of plant species. Plant species were scored present or absent is the ten 5m x 5m sub-plots. Using the formulae by Grieg-Smith (1964), the frequencies and relative abundances were calculated using the following relations:

$$\text{Frequency (X)} = \frac{\text{Number of quadrats with species X}}{\text{Total number of quadrats used}}$$

$$\text{Percentage Relative Abundance} = \frac{\text{Frequency of species X}}{\text{Sum of frequency values of all species}} \text{ X } 100$$

Percentage relative abundances were then expressed as domain values as shown below:

Percentage		Domain Value	Remarks
8.1 – 10.0	=	**5**	Constantly present
6.1 – 8.0	=	**4**	Mostly present
4.1 – 6.0	=	**3**	Often present
2.1 – 4.0	=	**2**	Seldom
0 – 2.0	=	**1**	Rare

3.3.4.2 Determination of Species Diversity

The diversity of plant species in the study sites was quantified using the Shannon-Wiener species diversity index (Blanc *et al*., 2000) calculated as follows:

$$\mathrm{H}' = -\sum_{i=1}^{s} pi \ln pi$$

Where:

Pi = proportion of the ‘i’th species
Ln *pi* =Natural log of *pi*
S = species richness

3.3.4.3 Determination of Species Similarity

The Jaccard’s index of similarity (*I*) which compares the degree of similarity of species between a pair of plot (Blanc *et al*., 2000) was calculated using the formulae below

$$I = \frac{C}{U_x + U_y + C} X\ 100$$

Where:

C = number of species common to both plot X and Y.

Ux = number of species found only in plot X.

Uy = number of species found only in plot Y.

3.3.5 Earthworm sampling

Earthworm extraction was done using 2% formaldehyde in 30cm x 30cm quadrats randomly distributed in the plots (Plate 8). The worms for each site were then collected, color-fixed in alcohol and preserved in formaldehyde. The specimens were sent to the Museum of the Department of Theoretical and Applied Biology, Kwame Nkrumah University of Science and Technology (KNUST) for identification.

PLATE 8: Earthworm sampling

3.3.6 Soil Sampling

By means of a drill auger, soil samples were taken randomly from the each of the ten 5m x 5m sub-plots at two depths; upper 20cm and 20-40cm. Soil samples were taken from each of the ten 5mx5m plots according to the depths, 0-20cm and 20-40cm from ten different spots by means of a screw auger and placed in clean plastic buckets. The samples were bulked according to depth, mixed thoroughly and a sub-sample taken to the laboratory. Each sample was labeled and tagged before sending to the laboratory for analysis.

3.4 PHYSICOCHEMICAL ANALYSIS

The soil samples were analyzed of the following:

1. *Fertility status* (pH, Ca, Mg, N, P, K, exch. Na, TEB, exchangeable acidity, CEC, %O.C, C:N ratio, available P & K)

2. *Soil water dynamics* through moisture content, hydraulic conductivity, density, porosity and particle size analysis (texture).

3. *Soil heavy metal* content (STSF-L and STSF-Bp only).

3.4.1. SOIL SAMPLE COLLECTION AND PREPARATION

At the laboratory, large clods were broken, stones and large plant residues removed. The samples were air-dried in dust-free location and sieved through a 2mm sieve and stored for both physical and chemical analyses.

3.4.2 PHYSICAL ANALYSIS

3.4.2.1 Soil Moisture

A 10g fresh soil sample (< 2mm) was weighed using an electric balance and placed in a metal can with lid. The specimen was oven-dried at 105^{o}C to constant weight, allowed to cool down for about 30 minutes in a desiccator and re-weighed. The amount of water originally present in the soil was determined using the following relation:

$$\%\ \text{Moisture in soil}\ (\theta\text{m}) = \frac{\text{Wet soil(g)} - \text{Dry soil(g)}}{\text{Dry soil(g)}}\ \text{x}\ 100$$

3.4.2.2 Volumetric water content (θv)

This was calculated by multiplying the soil water content by the bulk density.

3.4.2.3 Bulk density and porosity determination

A 5cm diameter thin-sheet metal tube of known volume (V) was driven into the soil using the hand sledge and block of wood. The soil around and beneath the ring were excavated with the trowel and carefully lifted out to prevent any loss of soil. Excess soil was trimmed, soil in the soil core removed and put in sample bags, sealed and labelled. Bulk density was then calculated as follows:

$$\text{Bulk density } (\delta) = \frac{\text{Oven} - \text{dry soil weight}}{\text{Volume of soil}} = \frac{\text{W(g)}}{\text{V(cm}^3\text{)}}$$

$$\text{Soil porosity}(\%) = 1 - \left(\frac{\text{Bulk density } (\delta)}{\text{Particle density}}\right) = 1 - \left(\frac{\delta}{2.65}\right)$$

3.4.2.4 Soil texture

The particle size distribution (texture) of the soil for each study site was determined by the hydrometer method. A 40 g air-dry soil (2-mm) was weighed into a 600-mL beaker and 60-mL dispersing solution (prepared by dissolving 40g sodium hexametaphosphate $\{(NaPO_3)_{13}\}$ and 10g sodium carbonate $\{Na_2CO_3\}$ in 1L distilled water) was added. The resulting solution was covered with a watch-glass and left to stand overnight.

Content of the beaker was transferred to high-speed electric soil dispersing stirrer with a cup receptacle and stirred at high speed for 3 minutes. The suspension was transferred into hydrometer jar, mixed thoroughly with a paddle and the hydrometer immediately inserted and reading taken at 40 seconds ($\mathbf{R_{sc}}$; silt and clay). Suspension is allowed to stand undisturbed and hydrometer reading taking at 4 hours ($\mathbf{R_c}$; clay only). Hydrometer reading for the Blank (containing dispersion solution but no soil) is also taken (**R_b**; blank). After the readings the suspension was sieved though a 50µm sieve and residue dried in an oven at 105°C overnight and weight determined. Calculations:

$$\% \text{ Clay} + \text{silt (w/w)} = \frac{(\text{Rsc} - \text{Rb})}{\text{weight of soil (g)}} \text{ x } 100$$

$$\% \text{ Clay (w/w)} = \frac{(\text{Rc} - \text{Rb})}{\text{weight of soil (g)}} \text{ x } 100$$

$$\% \text{ silt (w/w)} = \{\% \text{ Clay (w/w)}\} - \{\% \text{ Clay} + \text{silt (w/w)}\}$$

$$\% \text{ sand (w/w)} = \frac{\text{weight of sand (g)}}{\text{weight of soil (g)}} \text{ x } 100$$

From the percentages of sand, silt and clay, the textural class of each soil sample was determined using the USDA textural triangle.

3.4.2.5 Hydraulic conductivity determination

The saturated hydraulic conductivity measurements were made in the laboratory using falling head permeameter method on the core samples for the various sites. Cylinder of the same diameter was fitted to the top of the core to allow imposition of a hydraulic head. The cores were soaked in water overnight or until saturated. A large empty can with perforated bottom was filled with fine gravel. The core was placed on the gravel supported by a plastic sieve. The whole system was placed over a sink in the laboratory and water was gently added to give hydraulic head in the extended cylinder. The fall of the hydraulic head *Ht* at the soil surface was measured as a function of time *t* using a water manometer with a meter scale. *Ks* was calculated by the standard falling head equation as:

$$\text{Ks} = \left(\frac{\text{A . L}}{\text{a . t}}\right)\ln\left(\frac{\text{Ho}}{\text{Ht}}\right)$$

Where:

A = surface area of the cylinder,

a = the surface area of the soil,

H_0 = initial hydraulic head and

L = length of the soil sample.

3.4.3 CHEMICAL ANALYSIS

3.4.3.1 Soil pH

The pH of the soil was potentiometrically measured as recommended by Mclean (1982) in a supernatant of 1:1 soil: liquid mixture using a HI 9017 microprocessor pH meter. 20g each of sample s were placed in a beaker, 20mL of distilled water added and stirred continuously with an electrode for 10 minutes. The suspension was allowed to equilibrate. The pH meter was then set using buffer solution of pH 4.0 at room temperature. The pH of the soil samples were obtained and recorded for each study site.

3.4.3.2 Organic carbon and organic matter determination

Wet oxidation method as recommended by Walkley and Black, (1934) was used to determine the percentage organic carbon of each soil sample. 2.0g of soil sample was weighed into a 500mL Erlenmeyer flask. 10mL of 1M potassium dichromate ($K_2Cr_2O_7$) was added by means of a pipette followed by 20mL of concentrate sulphuric acid (H_2SO_4). The conical flask was swirled for about a minute in a fume chamber (owing to evolution of gas) and allowed to stand for 30minutes. 200mL of distilled water was added and swirled to ensure thorough dilution. 10mL phosphoric acid (H_2PO_4), 0.2g NaF and 1mL of diphenylamine indicator were added. The excess Cr_2O_7in the suspension was back titrated with 0.5 M ferrous sulphate solution. Near the end point, the purple color changes rapidly to green. A blank solution was also prepared in the same way. The percentage carbon of soil samples from each horizon was determined from the formula below:

$$\% \textbf{ Total Organc Carbon} = \frac{(\mathrm{B} - \mathrm{S}) \text{ x Molarity } \mathrm{FeSO_4} \text{ x } 0.003 \text{ x } 100}{\text{weight of soil}} \text{ x}1.2987$$

$$\% \textbf{ Organic matter} = \%\text{Organic carbon x } 1.724$$

Where:

B = Blank titre value

S = Sample titre value

0.003 = $12/4000$ = millequivalent weight of carbon

1.2987 = $100/77$ = the factor converting the carbon actually oxidized to total carbon

1.724 = $100/58$ = the factor converting the % organic carbon to organic matter based on the assumption that soil organic matter contains 58% carbon.

100 = the factor to convert from decimal to percent

3.4.3.3 Total Nitrogen

Total nitrogen of each soil sample was determined by the Kjeldahl digestion and distillation procedure as described in Ryan *et al*. (2001). 0.2g of soil sample was weighed into a into a 100-mL calibrated digestion tube. 5.0 g catalyst mixture, a few pumice boiling granules, 15 mL concentrated sulfuric acid were added in the fume hood), swirled carefully and allowed to stand overnight. The tubes racks were placed in the block-digester and temperature slowly increase to about 370°Cfor about 3 hours. 10 mL aliquot was pipetted into a 100-mL distillation flask, and 10mL of 10 N sodium hydroxide (NaOH) solution added and distilled to obtain ammonium sulphate. When about 35mL distillate had been collected, titration against standardized 0.01 N H_2SO_4 using Bromocresol green as an indicator until color changes from green to pink. Percentage nitrogen of soil sample from each horizon was determined using the following formula:

$$\%\mathbf{N} = \frac{\mathbf{(V - B) x N x R x 14.01 x 100}}{\mathbf{Wt x 100}}$$

Where:

V = volume of 0.01 N H2SO4 titrated for the sample (mL)

B = digested blank titration volume (mL)

N = normality of H_2SO_4 solution

14.01 = atomic weight of N

R = ratio of total volume of the digest and the digest volume used for distillation

3.4.3.4 C: N RATIO

Carbon to nitrogen ration was calculated from organic carbon and total nitrogen for each sample.

3.4.3.5 Exchangeable Cations

Exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were determined in 1.0 M ammonium acetate (NH_4OAc) extract (Ryan *et al.*, 2001) whiles the exchangeable acidity (Al^{3+} and H^+) was determined in 1.0 M KCl extract as described by Page (1982).

3.4.3.5.1 Exchangeable Bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+)

5g of soil sample was placed into 100mL extraction bottle. 20mL of ammonium acetate was added, stirred and allowed to stand overnight. By means of Whatman no. 42 filter paper, the suspension was filtered into a 100mL volumetric flask. The residue was successively leached with 20mL ammonium acetate until nearly 100mL of filtrate had been collected.

3.4.3.5.1.1 Determination of Ca^{2+}

25mL of the ammonium acetate extract was placed in a 250mL conical flask and diluted with distilled water to 150mL mark. 10 drops each of KCN, NH_2OH, HCl and triethanolamine were added. Sufficient amount of 10% NaOH was added to raise the pH to 12 and 5 drops of calcon indicator were added. The solution was titrated with 0.005 EDTA (Ethylene Diamine Tetra Acetate Acid).

3.4.3.5.1.2 Determination of Mg^{2+}

25mL of the ammonium acetate extract was placed in a 250mL conical flask and diluted with distilled water to 100mL mark. 20mL of 20% tungstate solution was added and sufficient buffer solution added to raise the pH to 10. The solutions were heated in a water bath and by means of Whatman No. 42 filter paper, the suspension was filtered into a 250mL volumetric flask. The residue was successively leached with 50mL of buffer solution. 10 drops each of KCN, NH_2OH, HCl $K_4Fe(CN)_6$ and triethanolamine (TEA) were added and allowed for some minutes. 10 drops of Erichrome Black T indicator (EBT) was added and titrated with 0.005 EDTA from red to a blue end point.

3.4.3.5.1.2 Determination of K^+ and Na^+

The flame photometer was calibrated by means of working standard of 0, 2, 4, 6, and 8, 10µg/mL of both sodium and potassium. Calibration curve of photometer reading against concentration of working standard was plotted. The equation of the curve for each was determined as follows:

$$\textbf{Potassium}: \quad y = 0.488x - 0.8648$$

$$\textbf{Sodium}: \quad y = 10.1x - 0.3333$$

Where:

x = emission and

y = concentration in parts per million (mg/Kg)

25mL of the ammonium acetate extract for each sample was aspirated and their emissions recorded. Using the calibration equations above, the concentrations of Na and K were determined.

3.4.3.5.2 Exchangeable Acids (Al^{3+} and H^+)

10g of soil was placed in a beaker and 30mL of 1M KCl was added, stirred and allowed to stand overnight. By means of Whatman No. 42 filter paper, the suspension was filtered into a 100mL volumetric flask. The Residue was successively leached with 10mL KCl until nearly 100mL of filtrate had been collected. 50mL of KCl extract was pipette into a 250mL conical flask. 5 drops of phenolphthalein indicator was added and titrated against 0.01M NaOH to the pink end point color.

3.4.3.5.3 Determinations based on Exchangeable cations

3.4.3.5.3.1 Total exchangeable base (TEB)

The total exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) for each horizon of soil sample were obtained from the exchangeable cations.

3.4.3.5.3.2 Effective Cation Exchange Capacity (ECEC)

ECEC was determined by the sum of exchangeable bases (calcium, magnesium, sodium and potassium) and exchangeable acidity (aluminium and hydrogen).

3.4.3.5.3.3 Percentage Base saturation (PBS)

The percentage base saturation of each soil sample was obtained as follows:

$$\% BS = \frac{Total\ exchangeable\ base}{ECEC} X\ 100$$

3.4.3.6 Determination of available phosphorus and potassium

Available phosphorus was determined by the Bray-1 method as described by Bray and Kurtz (1945). 5 g air-dry soil was weighed into a 250-mL Erlenmeyer flask and 50mL of extraction solution (15mL of 37mL/L NH_4F + 25mL HCl in 460mL distilled water). The flask was closed with a rubber stopper, and shaken for 30 minutes on a shaker at 200 - 300 rpm. The solution was filtered through a Whatman No. 40 filter paper, and 10mL clear filtrate pipetted into a 50-mL volumetric flask. Bray's solution extracts the phosphorus and potassium from the soil sample into the suspension

3.4.3.6.1 Determination of available P

5mL of the filtrate was pipetted into a beaker and a coloring reagent (0.025g ascorbic acid powder was added to it. The solution was allowed to stand for 30 minutes for a blue colour to develop. The spectrometer was calibrated by means of working standard of 0.1, 0.2, 0.4, 0.6, 0.8 and 1.0 µgP/mL. The absorbance of phosphorus in each soil sample was then determined using the spectrometer. The equation of the calibration curve was used to determine available P (ppm) for each sample as follows:

$$y = 0.014 + 0.0992x$$

Where:

x = absorbance

y = concentration in parts per million (mg/Kg)

3.4.3.6.2 Determination of available K

Flame photometry was used to determine the emission of potassium and recorded. Prior to this, the flame photometer was calibrated by means of working standard of 0, 2, 4, 6, and 8, 10µgK/mL. Calibration curve of emission against concentration of working standard was plotted. The concentration of potassium in each sample was obtained using equation of the curve for each was determined as follows:

$$y = 0.014 + 0.0992x$$

Where:

x = emission

y = concentration in parts per million (mg/Kg)

3.5 STATISTICAL ANALYSIS

A one-way analysis of variance (ANOVA) in complete randomized block designs was used to analyze the data. The Least Significant Difference (LSD) method was used to compare treatment means at p = 0.05. All statistics were performed using Genstat Discovery Edition 2 (2009).

PLATE 9: Stunted *Ceiba pentandra* at STSF-Bp

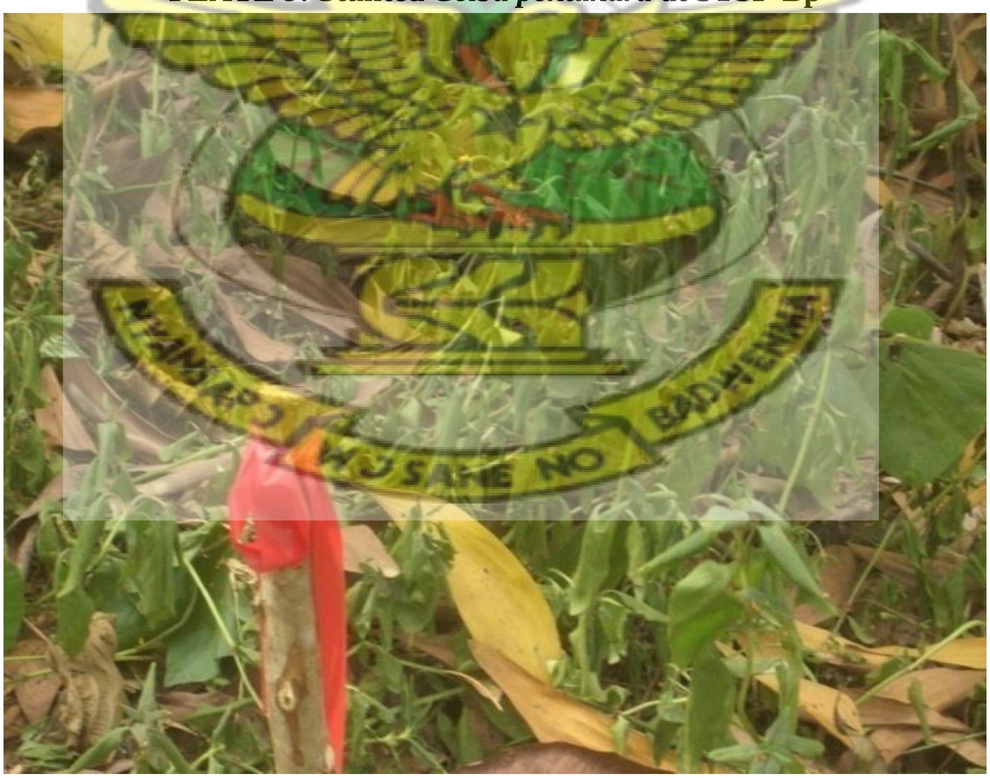


PLATE 10: Withering undergrowth at TMS

CHAPTER FOUR

4.0 RESULTS

4.1 FLORISTIC COMPOSITION

4.1.1 Plant species and families

4.1.1.1 Species and family richness

Both the species richness and family to which the sampled flora in the study sites belong follow the trend RHR-F> TMS> STSF-Bp> STSF-L as presented in Fig. 1.

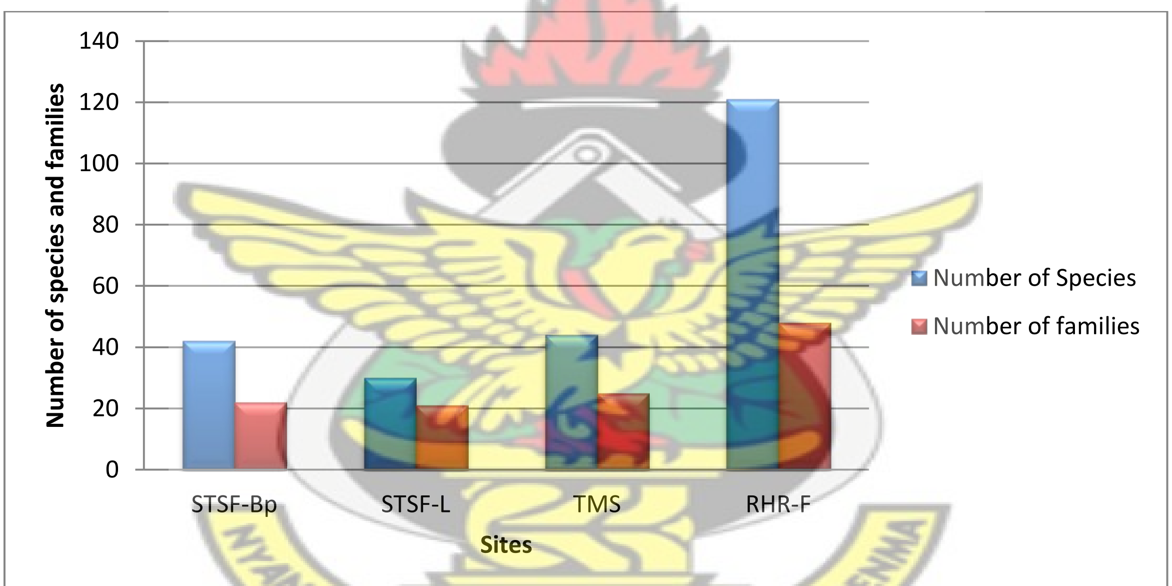


Fig. 1: Species richness of the studied areas.

4.1.1.2 Dominant plant families

The dominant plant families in the study sites are Euphorbiaceae > Apocynaceae > Mimosaceae > Graminae = Papilionaceae = Rubiaceae = Sterculiaceae > Annonaceae = Caesalpiniaceae as shown in table 1.

Table 1.: Dominant Plant families

FAMILY	NUMBER OF SPECIES
ANNONACEAE	6
EUPHORBIACEAE	13
APOCYNACEAE	9
MIMOSACEAE	8
GRAMINEAE	7
PAPILIONACEAE	7
RUBIACEAE	7
STERCULIACEAE	7
CAESALPINIACEAE	6

4.1.2 Plant diversity

The diversity of species by Shannon-Wiener index of diversity for the study sites is RHR-F (3.756) > STSF-Bp (2.392) > TMS (2.375) >STSF-L (1.844) as observed in Fig. 2.

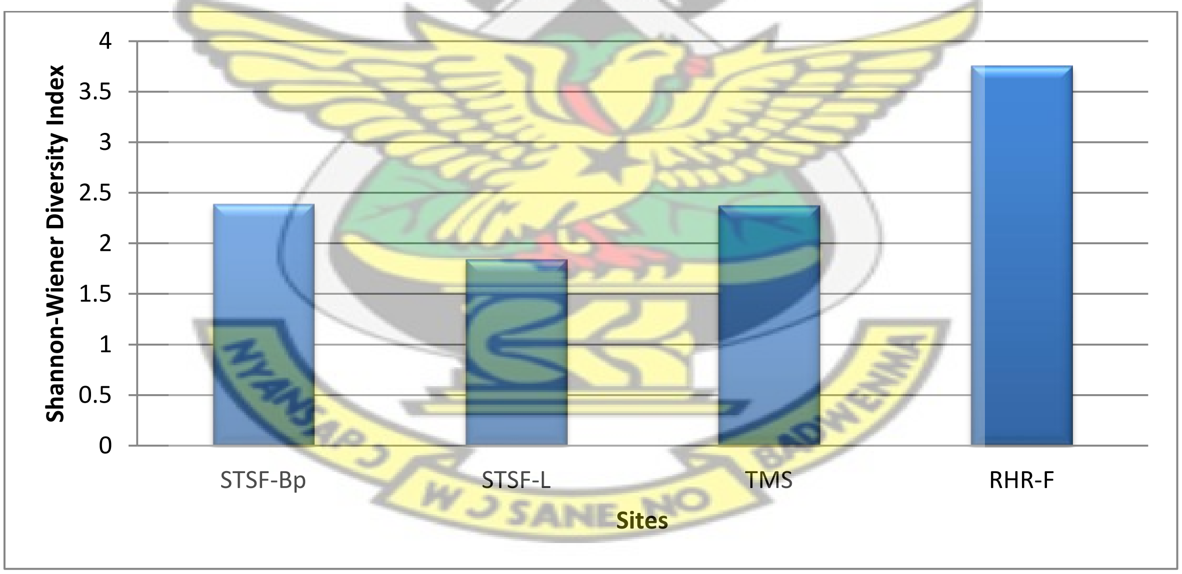


Fig. 2: Species diversity of studied area by Shannon diversity index.

4.1.3 Plant species similarity

Similarity of plant species of revegetated sites to reference forest (RHR-F) and baseline data (TBL or LBL) by Jaccard's index of similarity is as shown in Fig. 3. The index was highest at TMS (TBL>RHR-F) showing that species at TMS compares more with baseline than RHR-F, followed by STSF-Bp (RHR-F>LBL) and least in STSF-L (LBL>RHR-F). It also showed LBL>TBL in terms of similarity with RHR-F.

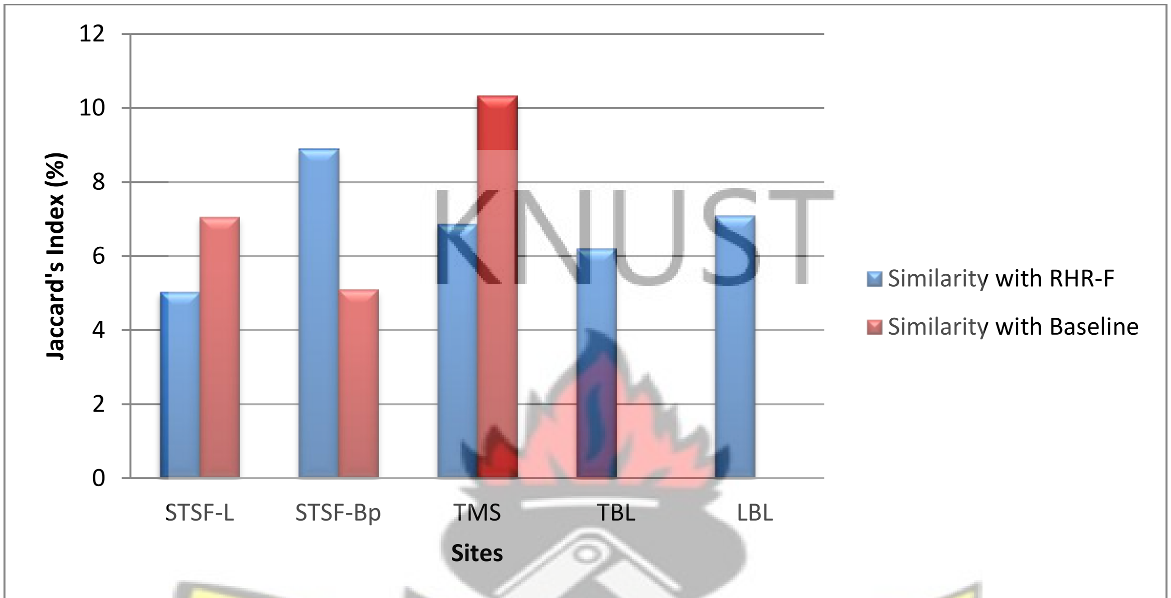


Fig. 3. : Species similarity by Jaccard's index

4.1.4 Plant density

Total plant density for the various study sites is observed to follow the trend STSF-Bp > RHR-F > STSF-L > TMS as shown in Fig. 4.

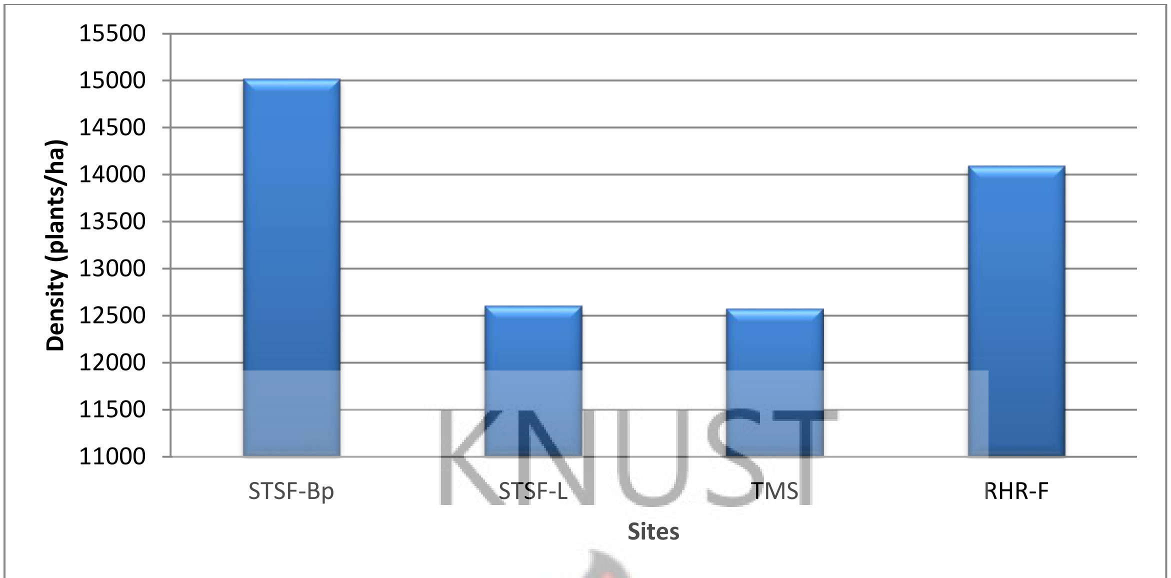


Fig. 4: Density of plant species in the studied areas.

4.1.5 Life Form

Percent cover of the seven different life forms (tree, shrub, liana, grass, climbers, ferns and herb) in the studied sites is presented Fig. 5. In all sites trees were the dominant life form (RHR-F > TMS > STSF-L > STSF-Bp). Herbs ranked second (TMS>STSF-L=STSF-Bp>RHR-F) followed by lianas (RHR-F > STSF-L > STSF-Bp > TMS) then grasses (STSF-Bp > TMS > STSF-L > RHR-F). Climbers, the next in rank, were higher in the three re-vegetated sites (STSF-L>STSF-Bp>TMS) compared to the undisturbed site RHR-F. Shrubs follow in the order TMS > RHR-F > STSF-L > STSF-Bp. Ferns, the least life form, were found in only two sites; STSF-Bp > RHR-F.

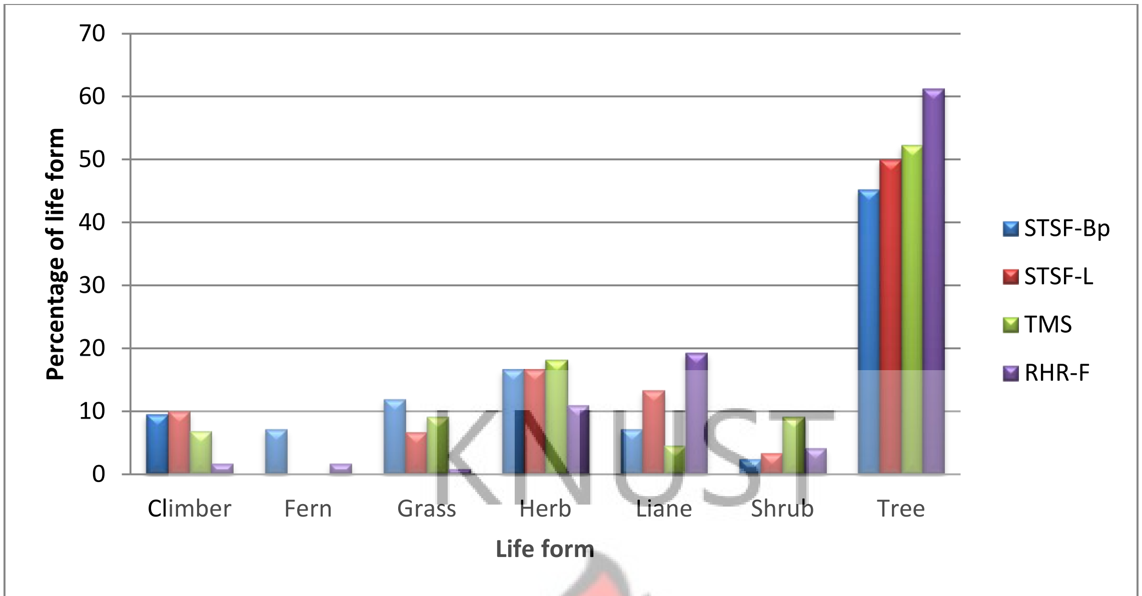


Fig. 5: Life forms of plants in the studied areas

4.1.6 Relative Abundance of species

The flora of the studied sites and their relative abundance are indicated in table 2. In total, 170 species in 143 genera and 59 families were identified in the study sites.

The most abundant species were *Acacia mangium* (Schumach & Thonn.) Hook. f., *Alchornea cordifolia* Schumach & Thonn Schumach & Thonn and *Harungana madagascariense* Lam. ex Poir (STSF BP); *Leucaena leucocephala* (Lam.) De Wit (STSF-L); *Sida acuta* Burm. f. (TMS) and *Angylocalyx oligophyllus*, *Baphia nitida* and *Griffonia simplicifolia* (RHR-F) (Table 2.)

The most abundant species for the various life forms were *Ipomoea involucrate (*6.40; STSF-Bp) for *climbers*, *Lycopodium cernum (*STSF-Bp) for ferns, *Axonopus compressus* (Sw.) P.Beauv. *(*STSF-L) for grasses, *Chromolaena odorata* (Linn.) King & Robinson, (STSF-L) for herbs, *Griffonia simplicifolia*, (RHR-F) for lianas, *Sida acuta* Burm. f., (TMS) for shrubs and, *Leucaena leucocephala* (Lam.) De Wit, (STSF-L) for trees (Table 2.).

Table 2.: Relative abundance of plant species in the studied areas and their corresponding baseline condition

FAMILY	PLANT SPECIES	STSF-Bp	STSF-L	TMS	RHR-F	TBL	LBL
ACANTHACEAE	*Asystasia gagentica* T. Anders	–	–	–	–	0.66	1.38
	Justicia flava (Forssk) Vahl	1.6	–	4.8	–	–	–
	Phaulopsis ciliata (Willd.) Hepper	0.8	–	–	–	–	–
ADIANTHACEAE	*Pityrogramona sp*	0.8	–	–	–	–	–
AGAVACEAE	*Dracaena surculosa* Lindl.	–	–	–	0.31	–	–
ANNONACEAE	*Cleistopholis patens* (Benth.) Engl. & Diels	–	–	–	0.31	–	–
	Enantia polycarpa Van Setten & Mass	–	–	–	0.31	–	–
	Greenwayodendron oliveri (Engl.) Verdc	–	–	–	0.61	–	–
	Monodora tenuifolia Benth.	–	–	–	0.92	–	–
	Polyalthea oliveri (Engl.) Verdc	–	–	–	–	1.72	1.55
	Xylopia staudtii Engl. & Diels	–	–	–	0.31	–	–
	Xylopia vilosa Chipp	–	–	–	0.31	–	–
APOCYNACEAE	*Alafia barteri* Oliv	–	–	–	0.31	–	–
	Alstonia boonei De Wild	0.8	6.8	0.8	–	–	–
	Baissia billonii Hua	–	–	–	1.22	–	–
	Funtumia africana (Benth.) Stapf	6.4	7.77	2.4	1.83	–	–
	Funtumia elastica (Preuss) Stapf	–	–	–	–	3.53	2.17
	Landolphia hirsuta (Hua) Pichon	–	–	–	0.31	–	–
	Landolphia micrantha (A.Chev) Pichon	–	–	–	0.31	–	–
	Landolphia oweriensis P.Beauv	–	–	–	–	3.42	1.36
	Parquentina nigrescens Afzel	–	1.94	–	–	–	–
	Picralima nitida (Staph) T. & H. Durand	–	–	–	–	5.23	3.64
	Rauvolfia vomitoria Afzel	6.4	0.97	1.6	2.75	1.66	1.72
	Tabernaemontana africana A. DC.	–	–	–	0.92	–	–
	Voacanga africana Stapf	–	–	–	0.31	3.49	1.82
ARACACEAE	*Colocasia esculenta* (Linn.) Schott	–	–	–	–	0.28	–
ARACEAE	*Cercestis afzelii* Schott	–	–	–	0.31	–	–
	Culcassia ivorensis Engl.	–	–	–	0.61	–	–
	Culcassia paviflora N. E. Br	–	–	–	0.31	–	–
	Culcassia striolata Engl.	–	–	–	1.53	–	–
ARECACEAE	*Laccosperma secundiflorum* O.Kuntze	–	–	–	–	2.99	–
ASCLEPIADACEAE	*Gongronema latifolia* Benth.	–	–	–	–	2.65	1.99
	Pergularia daemia (Forssk.) Chiov.	–	–	–	–	–	0.76
	Secamone afzelii (Schult.) K.Schum	–	1.94	0.8	–	1.79	2.43
ASTERACEAE	*Aspilia africana* (Pers.) C.D. Adams	–	–	–	–	0.56	–

Table 2. Continued

FAMILY	PLANT SPECIES	STSF-Bp	STSF-L	TMS	RHR-F	TBL	LBL
ASTERACEAE	*Chromolaena odorata* (Linn.) King & Robinson	–	7.77	1.6	–	1.62	3.02
ASTERACEAE	*Synodrella nodiflora* (Linn.) Gaerth.	–	–	0.8	–	1.11	–
	Vernonia andohii C.D. Adams	–	–	–	–	1.11	–
BOMBACACEAE	*Bombax bounopozense* P.Beauv	0.8	1.94	–	0.31	–	–
	Ceiba pentandra (Linn.) Gaertn	–	0.97	0.8	–	–	0.77
BROMELIACEAE	*Ananas comosus* (Linn.) Merill.	–	–	–	0.61	1.5	2.31
BURSERACEAE	*Canarium schweinfurthii* Engl.	–	–	–	0.61	–	–
	Dacryodes klaineana (Pierre) H.J. Lam	–	–	–	–	0.29	2.92
CAESALPINIACEAE	*Anthonotha macrophylla* P.Beauv.	–	–	–	1.53	–	–
	Berlinia occidentalis Keay	–	–	–	1.22	–	–
	Daniellia thurifera Bennett	0.8	–	–	–	–	–
	Griffonia simplicifolia (Vahl ex DC.) Baill	–	–	–	3.06	5.21	3.23
	Senna occidentalis (L.) Link	–	–	0.8	–	–	–
	Senna siamia (Lam.) H.S. Irwin & Barneby	–	6.8	3.2	–	–	–
CELASTRACEAE	*Hippocratea vignei* Hoyle	0.8	–	–	0.31	–	–
	Salacia owabiensis Hoyle	–	–	–	0.31	–	–
	Salacia pallescens Oliv.	–	–	–	0.31	–	–
CERCROPIACEAE	*Myrianthus arboreus* P.Beauv	–	–	–	–	2.1	2.92
CHRYSOBALANACEAE	*Parinari curatellifolia* Planch ex Benth	–	–	–	–	1.5	–
COMBRETACEAE	*Anogeisus leiocarpus* Guill. & Perr	–	–	–	0.31	–	–
	Combretum racemosum P.Beauv.	–	–	–	0.31	–	–
	Combretum zenkeri Engl. & Diels	–	–	–	0.61	–	–
	Terminalia ivorensis A.Chev.	–	–	–	–	–	0.61
	Terminalia superba Engl. & Diels	–	0.97	2.4	–	–	–
COMMELINACEAE	*Commelina benghalensis* Linn.	–	–	–	0.31	–	0.77
	Palisota hirsuta (Thunb.) K. Schum	–	–	–	0.31	2.79	1.76
	Tradescantia sp.	–	–	–	–	–	0.73
CONNARACEAE	*Ageleae nitida* (Lam) Baill	–	–	–	1.22	–	–
	Cnestis ferruginea Vahl ex DC.	–	–	–	1.22	–	2.07
CONVOLVULACEAE	*Calycobolus africanus* (G.Don) Heine	–	–	–	1.83	–	–
	Ipomoea involucrata P.Beauv.	6.4	–	–	–	–	–
CUCURBITACEAE	*Momordica cabraei* (Cogn.) Jeffrey	–	–	0.8	–	–	–
CYPERACEAE	*Cyperrus spp*	3.2	–	–	–	–	–
DICHAPETALACEAE	*Dichapetalum toxicarium* (G.Don) Baill	–	–	–	0.92	–	–
DIOSCOREACEAE	*Dioscorea bulbifera* Linn.	–	–	–	0.61	–	–

Table 2. Continued

FAMILY	PLANT SPECIES	STSF-Bp	STSF-L	TMS	RHR-F	TBL	LBL
DIOSCOREACEAE	*Dioscorea praehensilis* Benth	–	1.94	0.8	0.92	–	–
DRACAENACEAE	*Sansievieria liberica* Ger. & Labr	–	–	–	–	–	2.92
EBENACEAE	*Diospyros kamerunensis* Gurke	–	–	–	–	0.29	–
EUPHORBIACEAE	*Alchornea cordifolia* Schumach & Thonn	8	0.97	1.6	–	3.38	1.77
	Antidesma laciniatum Mull Arg.	–	–	–	0.31	–	–
	Bridellia attrovirides Mull Arg.	–	–	–	0.31	–	–
	Bridellia ferruginea Pierre ex Hutch	–	–	–	–	0.56	–
	Discoglypremna caloneura (Pax.) Prain	–	–	0.8	–	–	–
	Excocaria guineensis (Benth) J. Leonard	–	–	–	2.75	–	–
	Macaranga barteri Mull Arg.	6.4	–	1.6	1.22	–	0.61
	Macaranga heterophylla Mull Arg.	0.8	–	0.8	0.31	–	–
	Maesobotrya barteri (Baill.) Hutch.	–	–	–	0.31	–	–
	Mallotus oppositifolius Mull Arg.	–	–	–	–	2.47	–
	Manihot esculenta Crantz.	–	–	–	–	1.63	2.27
	Mareya micrantha (Benth) Mull Arg.	–	–	–	–	1.16	–
	Margaritaria discoidea (Baill.) Webster	–	–	–	0.92	–	–
	Phyllanthus amarus Mull Arg.	0.8	2.91	4.8	–	–	–
	Phyllanthus muellerianus (O.Ktze) Exell	–	–	0.8	–	–	–
	Ricinodendron heudelotii (Baill.) Pierre ex Pax	–	–	–	–	–	0.75
	Tetrorchidium didymostemon (Baill.) K. Hoffm	0.8	–	–	1.83	–	–
	Uapaca guineensis Mull Arg.	–	–	–	0.31	–	–
GALVACEAE	*Psidium guajava* Linn.	–	–	4	–	–	–
GRAMINEAE	*Axonopus compressus* (Sw.) P.Beauv.	2.4	8.74	4	–	–	–
	Brachiaria deflexa (Schumach) C.E. Hubb. ex Robyns	0.8	4.85	5.6	–	0.28	–
	Cynodon dactydon L.Pers.	2.4	–	–	–	–	–
	Leptaspis cochleata Thwaites	–	–	–	0.61	–	–
	Oplesmanus burmannii (Retz.) P.Beauv.	0.8	–	1.6	–	–	–
	Panicum maximum Jacq.	0.8	–	1.6	–	–	–
GUTTIFERAE	*Allanblackia parviflora* A. Chev.	–	–	–	0.61	–	–
	Garcinia afzelii Engl.	–	–	–	–	–	0.61
	Harungana madagascariense Lam. ex Poir	8	0.97	0.8	–	–	–
ICACINACEAE	*Chlamydocarya macrocarpa* A.Chev	–	–	–	0.92	–	–
	Rhaphidiostytis cordifolia (Schumach) Jeffrey	–	–	–	0.92	–	–
IRVINGIACEAE	*Irvingia gabonensis* (Aubry-Lecomte) Baill	–	–	–	–	1.5	–
IXONANTHACEAE	*Phyllocosmus africanus* **(Hook. f.) Klotzsch**	–	–	–	0.92	–	–

Table 2. Continued

FAMILY	PLANT SPECIES	STSF-Bp	STSF-L	TMS	RHR-F	TBL	LBL
LAURACEAE	*Beilschmiedia manni* (Meisn.) Benth & Hook. f.	–	–	–	0.31	–	–
LECYTHIDACEAE	*Napoleona vogelii* Hook & Planch	–	–	–	1.22	–	–
LECYTHIDACEAE	*Petersianthus macrocarpus* (P.Beauv.) Liben	–	–	–	0.61	–	–
LOGANIACEAE	*Anthocleista nobilis* G.Don	0.8	0.97	–	0.31	–	–
	Spigelia anthelmia Linn.	–	0.97	1.6	–	–	–
	Strychnos floribunda Gilg.	–	–	–	0.31	–	–
LYCOPODIACEAE	*Lycopodium cernum*Linn.	3.2	–	–	–	–	–
	Lygodium macrophylla (Cav.) R.Br	–	–	–	–	3.07	1.21
MALPIGHIACEAE	*Acridocarpus smeathmanii* (DC.) Guill & Perr.	–	–	–	0.31	–	–
MALVACEAE	*Sida acuta* Burm. f.	–	0.97	7.2	–	–	–
MARANTACEAE	*Hypselodelphys poggeana* (K. Schum) Milne-Redh.	–	–	–	2.14	–	–
	Hypselodelphys triangulare Jongkind Ined.	–	–	–	0.61	–	–
	Marantocloa lucantha (K. Schum) Milne-Redh.	–	–	–	0.31	–	–
	Marantocloa mannii (K. Schum) Milne-Redh.	–	–	–	2.45	–	–
	Thalia geniculata Linn.	–	–	–	–	2.66	0.74
	Thaumatococcus daniellii (Bennett) Benth	–	–	–	0.61	–	–
MELASTOMATACEAE	*Dissotis rotundifolia* (Sm.) Jacq.-Fel.	1.6	0.97	–	–	–	–
MELIACEAE	*Carapa procera* DC.	–	–	–	0.92	–	–
	Cedrella odorata Linn.	0.8	–	–	–	–	–
	Entandrophragma angolense (Welw.) DC.	–	–	–	0.92	–	–
	Entandrophragma cylindricum (Sprague)	–	–	–	–	–	0.77
	Trichilia monadelpha (Thonn.) J.J. de Wilde	–	1.94	0.8	2.75	1.11	–
MENISPERMACEAE	*Dioscoreophyllum volkensii* Engl.	–	–	–	0.31	–	–
	Sphenocentrum jollyanum Pierre	–	–	–	2.14	–	–
MIMOSACEAE	*Acacia mangium* (Schumach & Thonn.) Hook. f.	8	7.77	4.8	–	–	–
	Albizia adianthifolia (Schumach) W.F. Wight	0.8	–	–	1.22	–	–
	Albizia zygia (DC.) J.F. Macbr.	0.8	–	0.8	0.92	–	–
	Calpocalyx brevibracteatus Harms	–	–	–	1.83	–	–
	Leucaena leucocephala (Lam.) De Wit	–	9.71	3.2	–	–	–
	Mimosa pudica Linn.	1.6	4.85	2.4	–	–	–
	Piptadeniastrum africana (Hook. f.) Brenan	–	–	–	1.83	–	0.61
MORACEAE	*Antiaris africana* A.Chev	–	–	–	–	3.62	2.1
	Antiaris toxicaria (Rumph ex Pers.) Leschen.	–	–	–	0.31	–	–
	Dorstenia elliptica Engl.	–	–	–	–	–	0.73
	Ficus exasperata Vahl	–	–	–	0.31	–	–

Table 2. Continued

FAMILY	PLANT SPECIES	STSF-Bp	STSF-L	TMS	RHR-F	TBL	LBL
MORACEAE	*Ficus sur* Forssk	–	–	–	0.31	–	–
	Musanga cercropoides F.Br	–	–	–	0.31	–	–
MUSACEAE	*Musa paradisiaca* Linn.	–	–	–	–	1.11	–
MYRISTICACEAE	*Pycnanthus angolensis* (Welw.) Warb.	–	–	–	1.22	2.33	0.61
NEPHROLEPDACEAE	*Nephrolepis cordifolia* (Linn.) C.Presl.	–	–	–	–	1.16	–
	Nephrolepis biserrata (Sw.) Schott	–	–	–	0.31	2.62	2.19
OLACACEAE	*Heisteria parviflora* Sm.	–	–	0.8	0.31	–	–
	Strombosia glaucescens Oliv	–	–	–	0.61	–	0.75
PALMACEAE	*Elaeis guineensis* Jacq.	2.4	–	5.6	0.61	2.29	3.25
	Raphia hookeri G. Mann & H. Wendl	–	–	–	0.31	–	–
PANDACEAE	*Microdesmis keayana* J.Leonard	–	–	–	0.31	–	–
	Microdesmis puberula J.Leonard	–	–	–	2.75	–	0.75
PAPILIONACEAE	*Angylocalyx oligophyllus* (Baker) Baker f.	–	–	–	3.06	–	–
	Baphia nitida Lodd	–	–	–	3.06	5.01	4.56
	Calopogonium mucunoides Desv.	4	5.83	5.6	–	–	–
	Centrocema pubescens Benth.	0.8	0.97	3.2	–	–	–
	Dalbergia afzeliana Baker f.	–	–	–	0.31	–	–
	Desmodium adscendens (Sw.) DC.	0.8	–	0.8	–	0.29	–
	Desmodium scopiurus (Poir) DC.	–	–	–	–	–	1.42
	Millettia thonningii (Schumach & Thonn.) Baker	–	–	–	–	–	2.25
	Millettia zechiana Harms	–	–	–	1.83	3.07	1.76
PASSIFLORACEAE	*Adenia cissampeloides* (Planch & Benth) Harms	–	–	–	0.31	–	–
	Adenia lobata (Jacq) Engl.	–	–	–	–	2.83	2.15
	Smeathmannia pubescens Soland ex R.Br	–	–	–	0.31	–	–
POACEAE	*Flagellaria guineensis* Schumach	–	–	–	–	–	0.61
	Setaria barbata (Lam.) Kunth	–	–	–	–	2.03	2.43
POLYGALACEAE	*Carpolobia lutea* G.Don	–	–	–	0.92	–	–
PTERIDACEAE	*Pteris multifida* Poiret	–	–	–	–	1.11	–
RUBIACEAE	*Craterispermum caudatum* Hutch	–	–	–	–	0.29	1.46
	Diodia scandens (Hiene & Sandwith)	2.4	0.97	–	–	–	–
	Geophila afzelii Hiern	–	–	–	0.61	–	–
	Geophila obvallata (Schumach) F.Didr.	–	–	–	0.61	–	–
	Mitragyna inermis Leroy	–	–	–	–	–	0.75
	Morinda lucida Benth	0.8	–	–	–	–	–
	Nauclea latifolia (De. Wild & T.Durand)	–	–	–	–	–	1.46

Table 2. Continued

FAMILY	PLANT SPECIES	STSF-Bp	STSF-L	TMS	RHR-F	TBL	LBL
RUBIACEAE	*Oxyanthus subpunctatus* (Hiern) Keay	–	–	–	–	1.5	–
	Pavetta mollissima Hutch & Dalziel	–	–	–	1.53	–	–
	Psychotia humilis Hiern	–	–	–	0.31	–	–
	Psydrax subcordata (DC.) Bridson	6.4	3.88	4	–	–	–
RUBIACEAE	*Rothmannia longiflorum* Salisb	–	–	–	–	–	0.75
RUTACEAE	*Citrus sinensis* Linn. Osb.	–	–	–	–	–	0.77
	Zanthoxylum gillettii (De. Wild) Waterman	–	–	–	0.31	0.29	–
SAPINDACEAE	*Allophylus africanus* P. Beauv. f.	–	–	–	0.31	–	–
	Blighia unijugata Baker	–	–	0.8	0.61	–	–
	Blighia welwitschii (Hierne) Radlk	–	–	–	0.31	–	–
	Cardiospermum grandiflorum Swartz	–	–	–	–	–	1.41
	Chytranthus cauliflorus (Hutch & Dalziel)	–	–	–	1.53	–	–
	Paullinia pinnata Linne.	–	–	–	–	–	0.97
SIMAROUBACEAE	*Hannoa klaineana* Pierre & Engl.	–	–	–	0.31	–	–
SMILACACEAE	*Smilax anceps* Willd.	0.8	–	–	–	–	–
	Smilax kraussiana Meisn.	1.6	0.97	–	1.83	–	3.06
STERCULIACEAE	*Cola caricifolia* G.Don	–	–	–	0.61	–	–
	Cola nitida (Vent.) Schott & Endl	–	–	–	1.22	–	–
	Nesogordonia papaverifera (A.Chev.) R.Capuron	–	0.97	–	–	–	–
	Sterculia oblonga Mast	–	–	–	–	–	1.54
	Theobroma cacao Linn.	–	–	–	1.53	1.16	1.22
	Triplochiton scleroxylon K.Schum	–	–	0.8	0.31	–	–
THELYPTERIDIACEAE	*Cyclosorus afer* Ching.	0.8	–	–	0.31	–	–
TILIACEAE	*Christiana africana* DC.	–	–	–	–	2.48	1.47
	Clappertonea ficifolia (Willd.) Decne	–	–	2.4	–	–	–
	Desplatsia chrysochlamys Mildbr. & Burret	–	–	–	0.61	–	–
	Glyphaea brevis (Spreng.) Monachino	–	–	–	0.31	–	–
	Grewia carpinifolia Juss	–	–	–	–	2.38	1.45
	Grewia molis P.Beauv.	–	–	–	0.31	–	–
ULMACEAE	*Celtis mildbraedii* Engl.	–	–	–	0.61	–	–
URTICACEAE	*Fleurya aestuans* (Linn.) Chew	–	–	–	–	–	0.61
VERBENACEAE	*Clerodendrum capitatum* (Willd) Thonn.	–	–	–	1.22	–	–
	Lantana camara Linn.	–	–	0.8	–	–	–
	Stachytarpheta cayennensis (Rich.) Vahl	0.8	–	4	–	–	–
	Stachytarpheta indica (Rich.) Vahl	0.8	–	–	–	–	–

Table 2. Continued

FAMILY	PLANT SPECIES	STSF-Bp	STSF-L	TMS	RHR-F	TBL	LBL
VERBENACEAE	*Tectona grandis* Linn. f.	–	–	0.8	–	–	–
	Vitex ferruginea Schumach & Thonn.	–	–	–	0.31	–	–
	Vitex rivolaris Gurke	–	–	–	0.31	–	–
VIOLACEAE	*Rinorea angustifolia* (Thou.) Baill.	–	–	–	0.31	–	–
	Rinorea oblongifolia (C.H. Wright) Marquand	–	–	–	0.61	–	–
VITACEAE	*Cissus adnata* Roxb.	–	–	–	–	0.29	1.46
ZINGIBERACEAE	*Costus afer* Ker - Grawl	–	–	–	–	–	0.61
ZYGOPHYLLACEAE	*Balanites aegyptica* Pierre & Engl	–	–	–	–	–	0.61

Color	% Relative Abundance	Remarks
	8.1 – 10.0	Constantly present
	6.1 – 8.0	Mostly present
	4.1 – 6.0	Often present
	2.1 – 4.0	Seldom
	0 – 2.0	Rare
	–	Not found
	Species introduced by active re-vegetation	

RHR-F Rex Haul Road Forest

TMS Tomento South Waste Rock Dump

STSF-L South Tailings Storage Facility – Legumes stands

STSF-Bp South Tailings Storage Facility – Borrow pit

T-BL Tomento Baseline flora (for TMS)

L-BL Lima Baseline flora (for STSF-L and STSF-Bp)

4.1.7 Species abundance

4.1.7.1 Relative abundance of species common to studied sites

4.1.7.1.1 Relative abundance of species common to all three sites

Species common to the three re-vegetated site were *Acacia mangium* (Schumach & Thonn.) Hook. f. (STSF-Bp > STSF-L > TMS), *Alchornea cordifolia* Schumach & Thonn (STSF-Bp > TMS > STSF-L), *Alstonia boonei* De Wild (STSF-L > STSF-Bp = TMS), *Axonopus compressus* (Sw.) P.Beauv. (STSF-L > TMS > STSF-Bp), *Brachiaria deflexa (*Schumach) C.E. Hubb. ex Robyns (TMS > STSF-L > STSF-Bp), *Calopogonium mucunoides* Desv. (STSF-L > TMS > STSF-Bp), *Centrosema pubescens* (TMS > STSF-L > STSF-Bp), *Funtumia africana* (Benth.) Stapf *(*STSF-L > STSF-Bp > TMS), *Harungana madagascariense* Lam. ex Poir (STSF-Bp > STSF-L > TMS), *Mimosa pudica* Linn. (STSF-L > TMS > STSF-Bp), *Phyllanthus amarus* Mull Arg. (TMS > STSF-L > STSF-Bp), *Psydrax subcordata* (DC.) Bridson (STSF-Bp > TMS > STSF-L), and *Rauvolfia vomitoria* Afzel (STSF-Bp > TMS > STSF-L) (Table 3.).

Summation of relative abundance of species common to all three sites reveals the trend STSF-L > STSF-Bp > TMS in terms of overall species performance on these sites (table 3.).

Table 3.: Relative performance of species common to STSF-Bp, STSF-L and TMS

FAMILY	PLANT SPECIES	STSF-Bp	STSF-L	TMS
APOCYNACEAE	*Alstonia boonei* De Wild	0.8	6.8	0.8
	Funtumia africana (Benth.) Stapf	6.4	7.77	2.4
	Rauvolfia vomitoria Afzel	6.4	0.97	1.6
EUPHORBIACEAE	*Alchornea cordifolia* Schumach & Thonn	8	0.97	1.6
	Phyllanthus amarus Mull Arg.	0.8	2.91	4.8
GRAMINEAE	*Axonopus compressus* (Sw.) P.Beauv.	2.4	8.74	4
	Brachiaria deflexa (Schumach) C.E. Hubb. ex Robyns	0.8	4.85	5.6
GUTTIFERAE	*Harungana madagascariense* Lam. ex Poir	8	0.97	0.8
MIMOSACEAE	*Acacia mangium* (Schumach & Thonn.) Hook. f.	8	7.77	4.8
	Mimosa pudica Linn.	1.6	4.85	2.4
PAPILIONACEAE	*Calopogonium mucunoides* Desv.	4	5.83	5.6
	Centrocema pubescens Benth.	0.8	0.97	3.2
RUBIACEAE	*Psydrax subcordata* (DC.) Bridson	6.4	3.88	4

4.1.7.1.2 Relative abundance of species common to STSF-Bp and STSF-L

Species common to STSF-L and STSF-Bp only were *Anthocleista nobilis* G.Don (STSF-L > STSF-Bp), *Bombax bounopozense* P. Beauv. (STSF-L > STSF-Bp), *Diodia scandens* (Hiene & Sandwith) (STSF-Bp > STSF-L), *Dissotis rotundifolia* (Sm.) Jacq.-Fel. (STSF-Bp > STSF-L), and *Smilax kraussiana* Willd. (STSF-Bp > STSF-L) (Table 4.).

Species common to STSF-Bp and TMS only were *Albizia zygia* (DC.) J. F. Macbr. (STSF-Bp = TMS), *Desmodium adscendens* (Sw.) DC. (STSF-Bp = TMS), *Elaeis guineensis* Jacq. (TMS > STSF-Bp), *Justicia flava* (Forssk) Vahl. (TMS > STSF-Bp), *Macaranga barteri* Mull Arg. (STSF-Bp > TMS), *Macaranga heterophylla* Mull Arg. (STSF-Bp = TMS), *Oplesmanus burmannii (Retz.)* P.Beauv. (TMS > STSF-Bp), and *Panicum maximum* Jacq. (TMS > STSF-Bp) (Table 4.).

As shown in table 4. summation of relative abundance of species common to STSF-Bp and STSF-L reveals the trend STSF-Bp > STSF-L in terms of overall species performance on the sites.

Table 4.: Relative performance of species common to STSF-Bp and STSF-L

FAMILY	PLANT SPECIES	STSF-Bp	STSF-L
BOMBACACEAE	*Bombax bounopozense* P. Beauv	0.8	1.94
LOGANIACEAE	*Anthocleista nobilis* G.Don	0.8	0.97
MELASTOMATACEAE	*Dissotis rotundifolia* (Sm.) Jacq.-Fel.	1.6	0.97
RUBIACEAE	*Diodia scandens* (Hiene & Sandwith)	2.4	0.97
SMILACACEAE	*Smilax kraussiana* Willd.	1.6	0.97

4.1.7.1.3 Relative abundance of species common to STSF-Bp and TMS

Species common to STSF-BP and TMS were *Justicia flava* (Forssk) Vahl (STSF-BP < TMS), *Macaranga barteri* Mull Arg. (STSF-BP > TMS), *Macaranga heterophylla* Mull Arg. (STSF-BP = TMS), *Oplesmanus burmannii* (Retz.) P.Beauv. (STSF-BP < TMS), *Panicum maximum* Jacq. (STSF-BP < TMS), *Albizia zygia* (DC.) J. F. Macbr. (STSF-BP = TMS), *Elaeis guineensis* Jacq. (STSF-BP < TMS) and *Desmodium adscendens* (Sw.) DC. (STSF-BP = TMS) (table 5.).

Summation of relative abundance of species common to STSF-Bp and TMS reveals the trend TMS > STSF-Bp in terms of overall species performance on these sites (table 5.).

Table 5.: Relative performance of species common to STSF-Bp and TMS.

FAMILY	PLANT SPECIES	STSF-Bp	TMS
ACANTHACEAE	*Justicia flava* (Forssk) Vahl	1.6	4.8
EUPHORBIACEAE	*Macaranga barteri* Mull Arg.	6.4	1.6
	Macaranga heterophylla Mull Arg.	0.8	0.8
GRAMINEAE	*Oplesmanus burmannii* (Retz.) P.Beauv.	0.8	1.6
	Panicum maximum Jacq.	0.8	1.6
MIMOSACEAE	*Albizia zygia* (DC.) J. F. Macbr.	0.8	0.8
PALMACEAE	*Elaeis guineensis* Jacq.	2.4	5.6
PAPILIONACEAE	*Desmodium adscendens* (Sw.) DC.	0.8	0.8

4.1.7.1.4 Relative abundance of species common to STSF-L and TMS

Species common to STSF-L and TMS only include *Ceiba pentandra* (Linn.) Gaertn (STSF-L > TMS), *Chromolaena odorata* (Linn.) King & Robinson (STSF-L > TMS), *Dioscorea praehensilis* Benth (STSF-L > TMS), *Leucaena leucocephala* (Lam.) De Wit (STSF-L > TMS), *Secamone afzelii* (Schult.) K. Schum (STSF-L > TMS), *Senna siamia* (Lam.) H. S. Irwin & Barneby (STSF-L > TMS), *Sida acuta* Burm. f. (TMS > STSF-L), *Spigelia anthelmia* Linn. (TMS > STSF-L), *Terminalia superb* (TMS > TSF-L), and *Trichilia monadelpha* (Thonn.) J. J. de Wilde (STSF-L > TMS) (Table 6.).

As shown in table 6. summation of relative abundance of species common to STSF-L and TMS reveals the trend STSF-L > TMS in terms of overall species performance on the sites.

Table 6.: Relative performance of species common to STSF-L and TMS

FAMILY	PLANT SPECIES	STSF-L	TMS
ASCLEPIADACEAE	*Secamone afzelii* (Schult.) K. Schum	1.94	0.8
ASTERACEAE	*Chromolaena odorata* (Linn.) King & Robinson	7.77	1.6
BOMBACACEAE	*Ceiba pentandra* (L) Gaertn	0.97	0.8
CAESALPINIACEAE	*Senna siamia* (Lam.) H. S. Irwin & Barneby	6.8	3.2
COMBRETACEAE	*Terminalia superba* A. Chev.	0.97	2.4
DIOSCOREACEAE	*Dioscorea praehensilis* Benth	1.94	0.8
LOGANIACEAE	*Spigelia anthelmia* Linn.	0.97	1.6
MALVACEAE	*Sida acuta* Burm. f.	0.97	7.2
MELIACEAE	*Trichilia monadelpha* (Thonn.) J. J. de Wilde	1.94	0.8
MIMOSACEAE	*Leucaena leucocephala* (Lam.) De Wit	9.71	3.2

4.1.7.2 Growth performance

4.1.7.2.1 Average height of trees introduced by active re-vegetation

The average height of *Acacia mangium* (Schumach & Thonn.) Hook. f. is TMS>STSF-Bp>STSF-L. *Leucaena leucocephala* (Lam.) De Wit is STSF-L>TMS, *Senna siamia* (Lam.) H. S. Irwin & Barneby TMS>STSF-L, *Ceiba pentandra (Linn.) Gaertn* TMS>STSF-L as shown in Fig. 6.

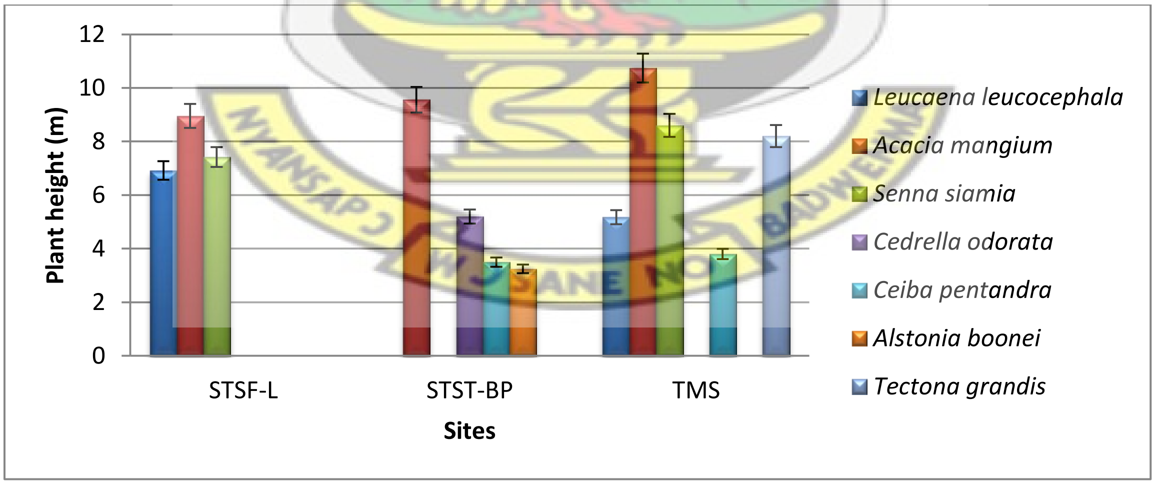


Fig. 6: Average height of introduced plant species for the re-vegetated sites

4.1.7.2.2 Average girth of trees introduced by active re-vegetation

The average girth at breast height (GBH) of *Acacia mangium* (Schumach & Thonn.) Hook. f. is TMS > STSF-L > STSF-Bp unlike the average height. *Leucaena leucocephala* (Lam.) De Wit is STSF-L >TMS, *Senna siamia* (Lam.) H. S. Irwin & Barneby TMS > STSF-L, *Ceiba pentandra* (Linn.) Gaertn TMS = STSF-L as shown in Fig. 7.

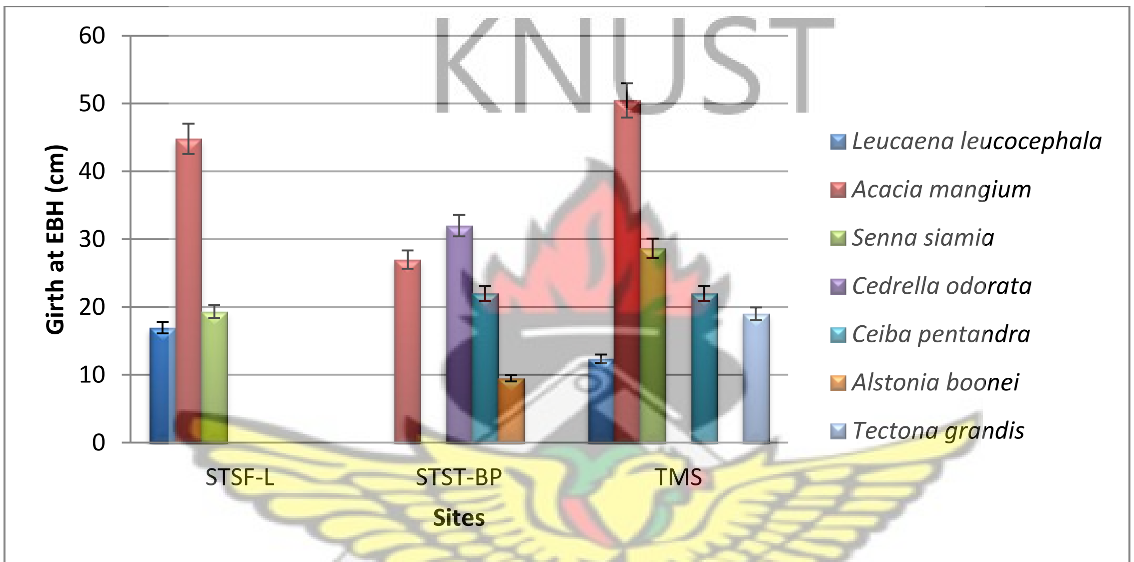


Fig. 7: Average girth at breast height (GBH) of introduced plant species for the re-vegetated sites.

4.1.8 Species restoration status

4.1.8.1 Species restoration status based on Baseline information

As shown in Fig. 8, with reference to their respective baseline condition, the number of species restored (re-introduced) follow the trend TMS > STSF-L > STSF-Bp whereas the number of species lost follow the trend STSF-Bp > STSF-L >TMS. The number of species that have been introduced (that did not exist at the site originally) follow the trend STSF-L > TMS > STSF-Bp.

Fig. 8: Species restoration status using baseline information as reference

4.1.8.2 Species restoration status based on Control site (RHR-F) information

As shown in Fig. 9, with reference to their respective the control site (RHR-F), the number of species restored (re-introduced) follow the trend STSF-L > TMS > STSF-Bp whereas the number of species lost follow the trend STSF-L >TMS > STSF-Bp. The number of species that have been introduced (that did not exist at the site originally) follow the trend TMS > STSF-Bp > STSF-L.

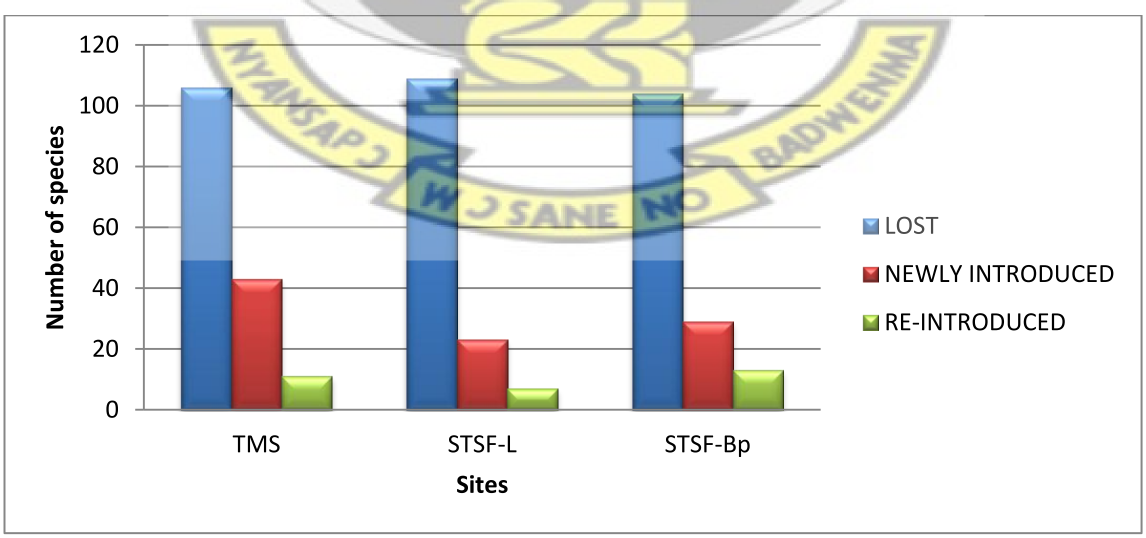


Fig. 9: Species restoration status using control site (RHR-F) as reference

4.2 Soil Fauna: Earthworms

Earthworm numbers as shown in Fig. 10 shows *Eudrilus eugeniae* (RHR-F > STSF-L > TMS > STSF-Bp), *Millsonia sp* (STSF-L > TMS > RHR-F) whiles *Benhania sp* were found only in STSF-L.

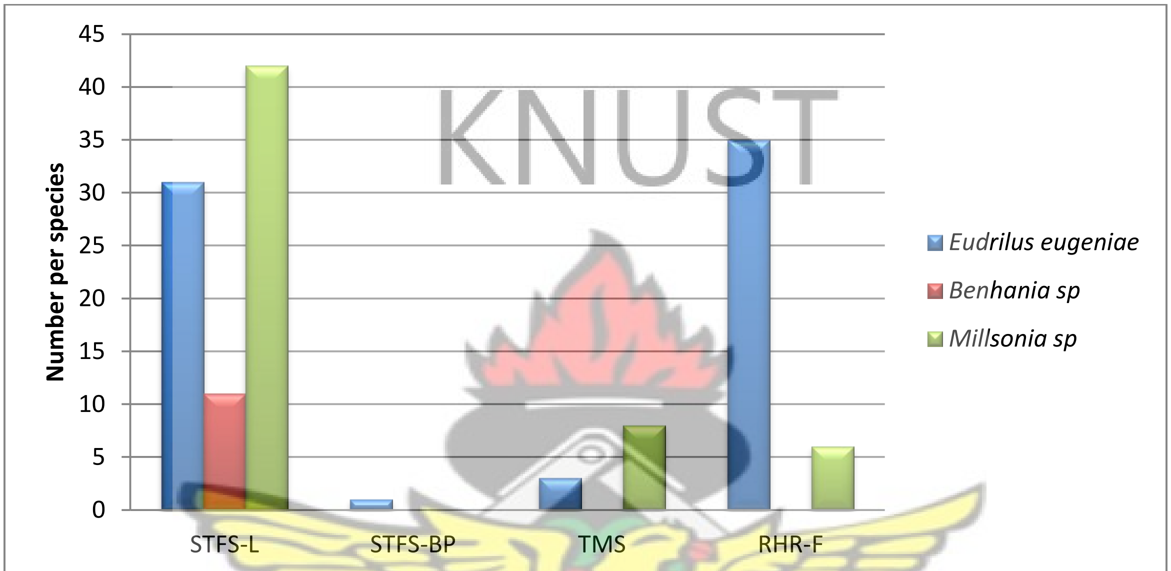


Fig. 10: Earthworm diversity and abundance of the re-vegetated sites

4.3 SOIL PHYSICOCHEMICAL CHARACTERISTICS

4.3.1 SOIL PHYSICAL CHARACTERISTICS

4.3.1.1 Soil moisture

For both depths, the highest values of soil moisture were recorded in STSF-L whiles the lowest values of soil moisture were in TMS. For both depths, STSF-L and STSF-Bp were significantly different from RHR-F (Table 7.).

4.3.1.2 Bulk density

For both depths, the highest values were recorded in TMS whiles the lowest were in STSF-L. For both depths only TMS was significantly different from RHR-F (Table 7.).

4.3.1.3 Porosity

For both depths, the highest values were recorded in STSF-L whiles the lowest was in TMS. For both depths all sites were not significantly different from RHR-F (Table 7.).

4.3.1.4 Hydraulic conductivity

For 0-20cm was highest in STSF-Bp and lowest in TMS but for 20-40cm, the highest was in STSF-L and lowest in TMS. For both depths all sites were not significantly different from RHR-F (Table 7.).

4.3.1.5 Texture

4.3.1.5.1 Clay

For 0-20cm was highest in STSF-Bp and lowest in STSF-L whiles for 20-40cm, the highest was in STSF-Bp and lowest in TMS. For both depths only STSF-Bp was significantly different from RHR-F (Table 7.).

4.3.1.5.2 Sand

For both depths, the highest values were recorded in TMS whiles the lowest were in STSF-Bp. For 0-20cm, none of the sites was significantly different from RHR-F. For 20-40cm depth, only TMS was significantly different from RHR-F (Table 7.).

4.3.1.5.3 Silt

For both depths, the highest values were recorded in STSF-L whiles the lowest were in TMS. For 0-20cm, only STSF-L was significantly different from RHR-F. For 20-40cm depth, both STSF-Bp and STSF-L were significantly different from RHR-F (Table 7.).

Table 7.: Soil physical characteristics at the study sites

Parameter	Depth	RHR-F	STSF-L	STSF-Bp	TMS	L.S.D(5%)	CV(%)
Moisture content (%)	(0-20)	14.8	17.8	17.1	7.5	2.15	5.4
	(20-40)	12.1	17.4	15.4	5.8	2.39	6.8
Bulk Density	(0-20)	0.98	0.98	1.1	1.5	0.28	7.6
	(20-40)	1.14	0.96	1.09	1.51	0.02	0.6
Porosity	(0-20)	0.63	0.63	0.58	0.43	0.12	7.4
	(20-40)	0.57	0.64	0.59	0.43	0.14	9.2
Hydraulic conductivity (m/s)	(0-20)	4.07 x10^{-05}	2.36 x10^{-05}	2.82 x10^{-05}	1.84 x10^{-05}	5.91 x10^{-05}	76.7
	(20-40)	8.40 x10^{-05}	4.75 x10^{-05}	9.78 x10^{-06}	4.35 x10^{-06}	1.92 x10^{-05}	19.0
%Clay	(0-20)	10	8.8	32	12	4.96	11.4
	(20-40)	12	8	26	4	3.24	9.3
%Sand	(0-20)	50.96	38.68	26.86	50.18	3.55	3.1
	(20-40)	47.38	36.98	25.96	57.62	2.26	1.9
%Silt	(0-20)	39.04	52.52	41.14	37.82	3.65	3.1
	(20-40)	40.62	55.02	48.04	38.38	3.02	2.4
Textural class	(0-20)	Loam	Silt Loam	Clay Loam	Loam		
	(20-40)	Sandy Loam	Silt Loam	Loam	Loam		

4.3.2 SOIL CHEMICAL CHARACTERISTICS

4.3.2.1 pH

For both depths, the highest pH values of 7.8 and 8.0 were recorded in STSF-L whiles the lowest value of 3.8 was at RHR-F. For both depths, all sites were significantly different from the control site (RHR-F) (Table 8.).

4.3.2.2 Exchangeable acidity

For both depths, TMS recorded the highest values whiles STSF-L was lowest. For both depths, all sites were not significantly different from RHR-F (Table 8.).

4.3.2.3 Percentage base saturation

For the upper 20cm, the highest was recorded in STSF-L and the lowest in TMS but for 20-40cm, the highest was recorded in STSF-L and lowest in STSF-Bp. For 0-20cm, only STSF-L was significantly different from RHR-F. For 20-40cm depth, both TMS and STSF-L were significantly different from RHR-F (Table 8.).

4.3.2.4 Total Exchangeable bases (TEB)

For 0-20cm was highest in STSF-L and lowest in TMS but for 20-40cm, the highest was in STSF-L and lowest in STSF-Bp. For both depths only STSF-L was significantly different from RHR-F (Table 8.).

4.4.2.5 Effective Cation Exchange Capacity (ECEC)

For both depths, the highest values were recorded in STSF-L while the lowest values were in STSF-Bp. Only STSF-L was significantly different for both levels (Table 8.).

4.3.2.6 Available Phosphorus

For the upper 20cm, the highest value was recorded in TMS whiles the lowest was recorded in STSF-Bp but for 20-40cm, the TMS recorded the highest and lowest was in STSF-L. For both depths, no site was significantly different from RHR-F (Table 8.).

4.3.2.7 Available potassium

For both depths, highest was recorded in STSF-L whiles STSF-Bp recorded the lowest. At 0-20cm depth, both STSF-L and TMS were significantly different from RHR-F but for 20-40cm, significant difference was in STSF-L only (Table 8.).

4.3.2.8 Exchangeable potassium

For both depths, highest values were recorded in STSF-L whiles the lowest values were recorded in STSF-Bp. Significant difference was in only STSF-L for both depths (Table 8.).

4.3.2.9 Exchangeable sodium

For both depths, STSF-Bp recorded highest values whiles the lowest values were recorded in TMS. None of the sites were significantly different from RHR-F for the upper 20cm. At 20-40cm, only STSF-Bp was significantly different (Table 8.).

4.3.2.10 Exchangeable magnesium

For 0-20cm, highest value was in STSF-Bp whiles the lowest was recorded in STSF-L. For 20-40cm, highest was in STSF-L and lowest in STSF-Bp. TMS and STSF-Bp were significantly different from RHR-F for 0-20cm. None of the sites was significantly different from RHR-F at 20-40cm (Table 8.).

4.3.2.11 Exchangeable calcium

For the upper 20cm depth, the highest was recorded in STSF-Bp whiles lowest recorded in TMS. For 20-40cm depth, the highest was recorded in STSF-L and the lowest recorded in STSF-Bp. For 0-20cm, STSF-L and STSF-Bp were significantly different from RHR-F. At 20-40cm depth, all sites were significantly different from RHR-F (Table 8.).

4.3.2.12 Total organic matter:

For 0-20cm depth, the highest was recorded in TMS whiles the lowest in STSF-Bp. For 20-40cm depth, the highest was recorded in TMS whiles both STSF-Bp and STSF-L recorded the lowest value. For both depths, all sites were significantly different from RHR-F (Table 8.).

4.3.2.13 Percentage nitrogen

For both depths, the highest values were recorded in TMS whiles both STSF-L and STSF-Bp recorded lowest value. For both depths, all sites were significantly different from RHR-F (Table 8.).

4.3.2.14 Percentage organic carbon

For 0-20cm, highest value was recorded in TMS whiles the lowest was in STSF-Bp. For 20-40cm depth, TMS recorded highest whereas both STSF-L and STSF-Bp recorded the lowest value. For both depths, all sites were significantly different from RHR-F (Table 8.).

4.3.2.15 C:N ration

For 0-20cm, STSF-L was highest and lowest was in STSF-Bp. For 20-40cm, the highest was recorded in TMS and lowest in STSF-Bp. For both depths, all sites were significantly different from RHR-F (Table 8.).

Table 8.: Soil chemical characteristics at the study sites

Parameter	Depth	RHRF	STSF-L	STSF-Bp	TMS	L.S.D(5%)	CV(%)
pH	**(0-20)**	3.8	7.8	4.0	4.7	0.43	2.7
	(20-40)	3.8	8.0	4.0	4.9	0.64	3.9
Exchangeable Acidity	**(0-20)**	0.94	0.40	0.80	0.9	0.23	9.3
	(20-40)	0.98	0.47	0.85	0.9	0.35	13.8
Base Saturation (%)	**(0-20)**	77.41	96.52	80.2	78.06	6.54	2.5
	(20-40)	81.22	96.14	81	84.66	3.29	1.2
Total Exch. Base	**(0-20)**	3.26	10.99	3.28	3.25	0.12	0.7
	(20-40)	4.10	11.73	3.59	4.96	1.42	7.3
Effective C.E.C. ($cmol_ckg^{-1}$)	**(0-20)**	4.20	11.39	4.08	4.15	0.31	1.6
	(20-40)	5.05	12.21	4.44	5.86	1.56	7.1
Available P (ppm)	**(0-20)**	7.49	1.52	0.56	1.99	0.02	0.2
	(20-40)	3.19	0.24	0.48	1.99	0.09	2
Available K (ppm)	**(0-20)**	73.65	103.78	33.48	80.35	0.17	0.1
	(20-40)	56.91	87.04	33.48	56.91	0.18	0.1
Exchangeable K ($cmol_ckg^{-1}$)	**(0-20)**	0.05	0.16	0.03	0.07	0.05	21.1
	(20-40)	0.07	0.19	0.07	0.14	0.07	18.1
Exchangeable Na ($cmol_ckg^{-1}$)	**(0-20)**	0.21	0.23	0.25	0.18	0.07	9.8
	(20-40)	0.23	0.23	0.32	0.22	0.03	3.3
Exchangeable Mg ($cmol_ckg^{-1}$)	**(0-20)**	1.35	1.2	2.4	2.05	0.13	2.3
	(20-40)	2.6	2.4	1.6	1.8	1.05	15.6
Exchangeable Ca ($cmol_ckg^{-1}$)	**(0-20)**	1.55	1.8	8.2	1	0.11	1.1
	(20-40)	1.2	9	1.6	2.8	0.37	3.2
Total Organic Matter (%)	**(0-20)**	1.25	0.82	0.57	1.14	0.13	4.3
	(20-40)	0.93	0.28	0.28	0.62	0.06	3.7
Nitrogen (%)	**(0-20)**	0.1	0.06	0.06	0.1	0.03	10.2
	(20-40)	0.07	0.04	0.04	0.06	0.04	25.8
Organic Carbon (%)	**(0-20)**	0.72	0.47	0.33	0.69	0.02	1.3
	(20-40)	0.54	0.16	0.16	0.36	0.03	2.7
C:N ratio	**(0-20)**	7.29	7.83	5.5	6.99	1.75	8
	(20-40)	7.86	4.4	4	6.23	5.32	29.7

4.3.3 PROGRESS IN SOIL PH AND EFFECTIVE CEC

Progress for pH in Fig. 11 shows that for STSF-L (2010 > 2007 = 2008), TMS (2007 > 2010 > 2008) and STSF-Bp (2008 > 2007 > 2010).

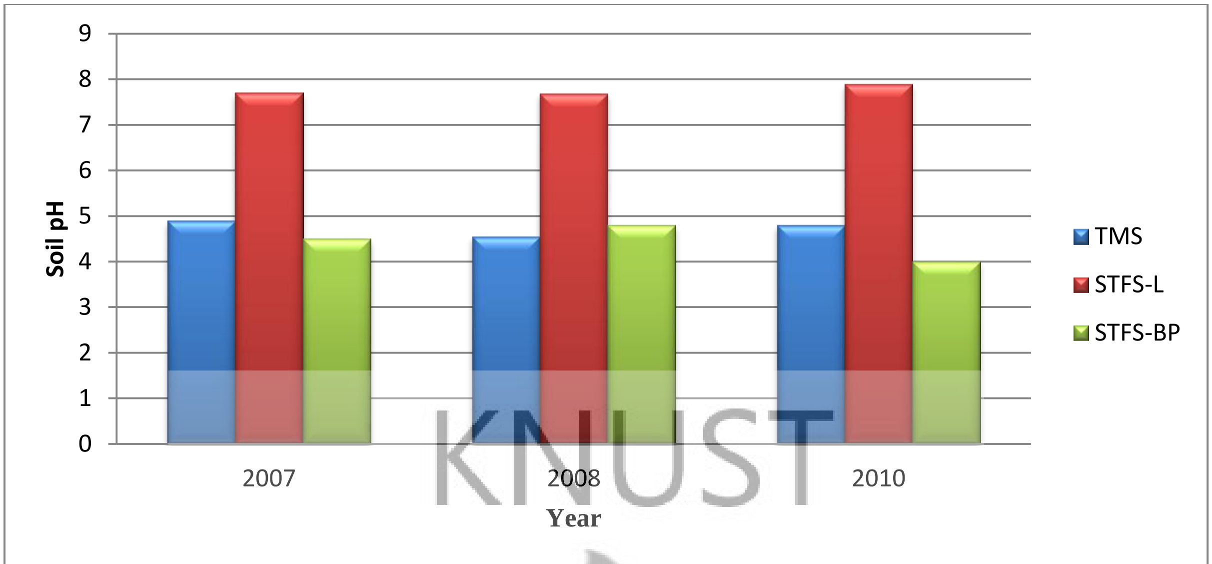


Fig. 11: Trend of pH for the re-vegetated sites

Progress for Effective cation exchange capacity as shown in fig 12 show the same trend for STSF-L, TMS and STSF-Bp (2007 > 2010 > 2008).

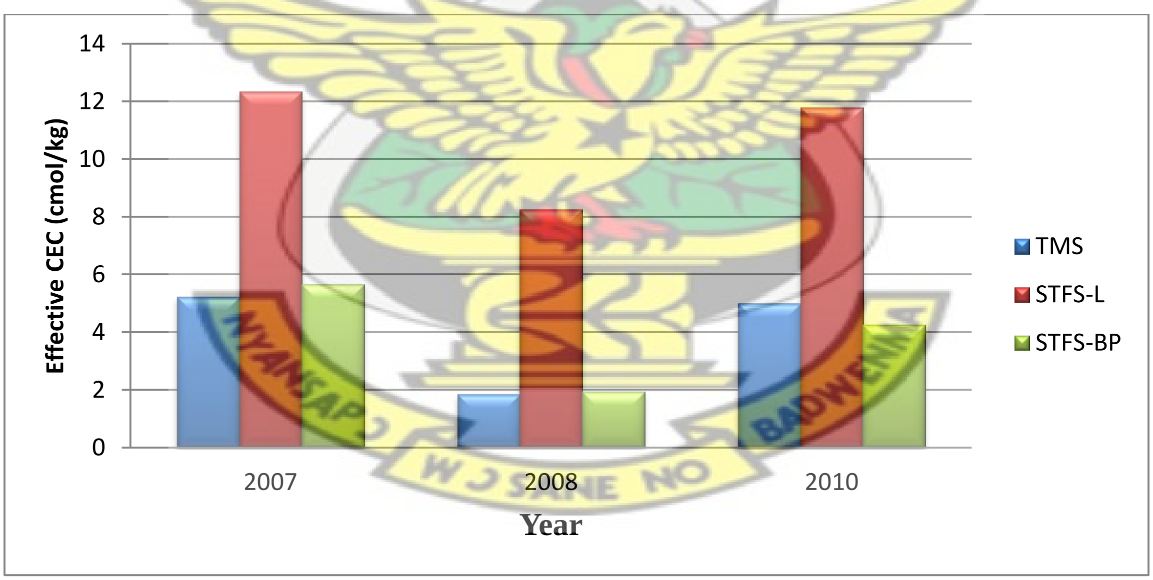


Fig. 12: Trend of Effective Cation Exchange Capacity for the re-vegetated sites

4.4 SOIL HEAVY METAL CONTENT

On both STSF-L and STSF-Bp, with the exception of Hg, Se and As, heavy metal contents for 2010 were lower than 2007. For Pb, Ag, Si and Co for both sites have dropped to trace levels (Table 9.).

On STSF-L, concentrations for Pb, Ni and As for 0-20cm were lower than 20-40cm but conversely, Zn and Cr had higher levels in 0-20cm depth than 20-40cm. On STSF-Bp, concentration of only Zn for 0-20cm was lower than 20-40cm whiles for Hg and As levels were higher at 0-20cm depth than 20-40cm (Table 9.).

From the interpretation key on heavy metal in appendix I, it is seen that levels of Pb, Cd, Zn, Se, Ni, and As are all in the range of non-contamination (Table 9.).

Table 9.: Trend of soil heavy metal content for STSF-L and STSF-Bp TMS for 2007 and 2010

YEAR	**2010**		**2007**	**2010**		**2007**
HEAVY METAL (ppm)	**STSF-L** (0-20)	**STSF-L** (20-40)	**STSF-L**	**STSF-Bp** (0-20)	**STSF-Bp** (20-40)	**STST-Bp**
Pb	Trace	Trace	3.29	Trace	Trace	3.29
Hg	7.55	12	<0.05	6.95	6.5	<0.05
Cd	0.1	0.1	0.94	0.2	0.2	1.41
Zn	9.25	5.95	16.5	3.1	4.65	12.9
Ag	Trace	Trace	<0.5	Trace	Trace	<0.5
Se	0.2	0.1	<0.05	0.1	0.1	<0.05
Cr	0.23	0.11	58.3	Trace	Trace	31.5
Ni	5.55	7.95	27.3	Trace	Trace	4
As	2.5	5.66	<0.05	3.4	2.31	<0.05
Si	Trace	Trace	115.7	Trace	Trace	1409
Co	Trace	Trace	17.9	Trace	Trace	3.76

CHAPTER FIVE

5.0 DISCUSSIONS

5.1 REVEGETATION METHODS, PRACTICES AND STRATEGIES

The revegetation methods, practices and strategies employed at AGL were found to follow standard practice both locally and internationally. For example, locally, in line with the National Land Policy for Ghana (Republic of Ghana, 1999) in that as much as possible, the destruction of the environment is prevented or minimized and where this is not possible, appropriate site-condition-based revegetation methods and practices are employed to ameliorate or restore same to the state it was before the disturbance. Internationally accepted standards in literature are part of methods employed at AGL. Examples include: stripping and stockpiling of quality topsoil (Hossner, 2000; Natural Resource Conservation Service, 2006); landform reconstruction and construction of drainage structures (Queensland Environment, 1995); reintroduction of native species that will not naturally return from soil seed pool (Alberta Environment, 2003); grasses and cover plants are used in erosion (Alberta Environment, 2003); seedlings are raised in nursery before transplanting in the prepared fields (Hossner, 2000); maintenance activities at AGL fall into all three categories of maintenance activities namely corrective, protective and manipulative (Hossner, 2000); monitoring of plant growth and soil quality (Munshower, 2000; Clark and Hutchinson, 2003) etc.

The results of the study clearly show that re-vegetation methods and practices used at Abosso Goldfields Ltd (AGL) follow the integrated revegetation approach described by Prach (2003) and Hossner (2000) in that passive and active revegetation are combined by directing natural succession. Evidence of directing natural succession is seen in maintenance practices such as scalping, coppicing and pollarding which promotes growth of species introduced by passive re-vegetation. With quite a lower number of species introduced by active re-vegetation, majority of the species were as a result of passive re-vegetation through soil seed stock, wind, rain, birds (e.g. *Psidium guajava* **L.** on TMS was possibly by birds) and other animals. This, according to TAdN Arundo Eradication Program (2004), has the advantage of ensuring the introduction of local genetic stock.

Re-vegetation practices in AGL treats the causes rather than the symptoms of degradation in line with Society of Ecological Restoration (2002) by eliminating or modifying the inhibiting factors that prevent natural restoration. Overburden materials removed prior to disturbance are characterized, stockpiled and reused as topsoil material as described in Natural Resources Conservation Service (2006). For instance, oxide substrate (highly weathered materials; Plate 3) is used to cap waste rock before addition of topsoil. Topsoil stockpiles are protected against erosion, dust generation, unnecessary compaction and contamination by noxious weeds, invasive species or other undesirable materials as recommended in Natural Resources Conservation Service (2006).

In line with Hossner (2000) and Alberta Environment (2003), a major factor contributing to success of re-vegetation projects in AGL is adequate site preparation which enhances initial plant establishment and increase soil stability. However, as observed in Plate 3, topsoil thickness is quite thinner as compared with the minimum thickness of four feet stated in Burger and Zipper (2002) and Munshower (2000).

Erosion control is very effective in AGL. Similar to what is stated in Natural Resources Conservation Service (2006) drainage ways (stone pitches) with sufficient capacity and stability have been constructed where slopes are very steep to carry runoff pool from the reclaimed area without causing erosion. The use of cover materials (*Pueraria* and various grasses) in erosion control is highly exploited. Competition with tree seedlings, the major problem with the use of cover materials, was observed in this study similar to Burger and Zipper (2002).To solve this problem, AGL makes use of two strategies same as recommended in Queensland Government (1995) namely: (l) planting of tree seedlings immediately after broadcasting seeds of cover material and (2) control of cover materials during maintenance stage. However, since runoff is the balance between rainfall influx and infiltration there is the need for exploration of erosion control measures that aim at improving infiltration rate such as green manuring or other measures to incorporate organic matter into the soil to enhance earthworm activities to improve soil porosity.

Regarding nutrient management, it was observed that the practice of the company was to supplement nutrients (especially nitrogen and phosphorus) with both organic (compost) and inorganic (compound fertilizer). AGL has a Compost Farm for production of compost from various organic wastes produced in the company.

With respect to species selection, apart from the use of timber and legume species, "only seed species that will not come back naturally from the soil seed bank", are "fast-growing" and do not require intensive methods to establish (Alberta Environment, 2003; Queensland Government, 1995) are selected for re-vegetation in AGL.

5.2 FLORISTIC COMPOSITION

Plant species diversity of the sampled sites was analyzed using the non-parametric measures of heterogenicity indicated that the data compared favorably with the existing baseline data.

5.2.1 Species diversity

In total, 170 species belonging to 59 families were identified. The diversity, in relation to area sampled, was very high compared to other researches (Addo-Fordjour *et al.*, 2009; Pappoe *et al.*, 2010; Hayat *et al.*, 2010). This diversity is attributable to the fact that there was no diameter cut-off and all life forms were sampled because for purposes of re-vegetation, all flora return is relevant and was to be considered.

The diversity of species by Shannon-Wiener index ranged from 1.84 (STSF-L) to 3.75 (RHR-F). The Shannon indices for the re-vegetated sites were lower than the undisturbed site; RHR-F. The index obtained for RHR-F was higher than that obtained by other works (3.43; Pappoe *et al*., 2010 and 3.6; Addo-Fordjour *et al*., 2009).

In line with Society for Ecological Restoration International Science & Policy Working Group (2004), results from the re-vegetated sites were compared to two reference vegetation (the undisturbed or control site; RHR-F and the baseline floral inventory; TBL and LBL) using Jaccard's index of similarity of plant species. The index showed that Tomento Baseline (TBL) was more similar to RHR-F than Lima Baseline (LBL). Using the index, compared with respective baseline condition, TMS ranked first followed by STSF-BP and least in STSF-L but compared with reference forest (RHR-F), STSF-BP ranked first followed by TMS whereas STSF-L was the least. It further showed that TMS was closer to baseline condition than the control site of the current study (RHR-F). STSF-Bp was more similar to the RHR-F than the baseline condition but conversely, STSF-L was closer to baseline condition than the control site of the current study (RHR-F).

5.2.2 Family dominance

Family dominance, one of the special features of tropical rain forests, was observed in this study. The present study confirmed that of Kochummen *et al.*, (1990) who reported that

Euphorbiaceae was the most prominent family. In terms of family and species distribution, TMS ranked first followed by STSF-Bp and least in STSF-L (Fig 4). These were, however, far lower than the number of species and family in the undisturbed site; RHR-F (Fig. 4).

5.2.3 Life form

Percentage cover of the seven different life forms showed that for all sites, trees were dominant. Since a forest is vegetation with trees dominating, it is logical that RHR-F had the highest proportion of trees whiles the re-vegetated disturbed sites show a progression by natural succession into forests. Similar to work by Addo-Fordjour *et al.*, (2009) in the Tinte Bepo forest reserve following anthropogenic disturbances and plant invasion, lianas ranked second in RHR-F. This confirms the baseline assessment that the area had been relatively disturbed by logging, artisanal mining and farming (AGL, 2003). That the climbers and grasses were higher in the three re-vegetated sites compared to the control forest is attributable to the use of *Pueraria* and grasses as cover materials for erosion control.

5.2.4 Species restoration status

Species restoration status using the baseline condition (Atyeo and Thackway, 2009) and undisturbed forest as references shows quite a lower number of species restored compared to species introduced or lost. The number of species restored (re-introduced) with reference to the control site (RHR-F) was higher than the number of restored species with reference to the respective baseline conditions. This trend is possibly due to "contemporary constraints and conditions may cause development along an altered trajectory" (Society for Ecological Restoration International Science & Policy Working Group 2004). For example, it was observed that no strict effort was made to ensure that the same topsoil is returned for use during surface preparation. Thus the major contributor of passive re-vegetation being soil seed pool, may be that of another disturbed site leading to situations where a larger number of species introduced did not exist previously. The lower number of restored species cannot be seen as a disincentive because AGL's re-vegetation goal for the studied areas was to leave a stable landform which can support usage of the local population for various uses such as farming but not to restore original plant community.

5.2.5 Relative Abundance of species

Compared with the work of Hayat *et al*. (2010) and Addo-Fordjour *et al*. (2008), the abundance figures for this study were higher indicating fair distribution of species. The most abundant species identified in the study sites was *Leucaena leucocephala* (Lam.) De Wit at STSFL. The most abundant species for STSF BP were *Acacia mangium* (Schumach & Thonn.) Hook. f., *Alchornea cordifolia* Schumach & Thonn and *Harungana madagascariense* Lam. ex Poir. That for TMS was *Sida acuta* Burm. f. *whiles Angylocalyx oligophyllus*, *Baphia nitida* and *Griffonia simplicifolia* were the most abundant species for RHR-F.

For the various life forms, the most abundant species were *Ipomoea involucrate for climbers, Lycopodium cernum* for *ferns, Axonopus compressus* (Sw.) P.Beauv. for *grasses, Chromolaena odorata* (Linn.) King & Robinson for *herbs, Griffonia simplicifolia*, for *lianas, Sida acuta* Burm. f., for shrubs, and *Leucaena leucocephala* (Lam.) De Wit, for trees. RHR-F contains important timber species such as *Piptadeniastrum africanum*, *Antiaris toxicaria* and *Celtis mildbraedii.* On TMS the most abundant species is *Sida acuta* Burm. f.. This is a sign of invasion by the noxious weed and so should be controlled immediately before it develops into a bigger problem.

Intraspecific plant competition was observed in this study in two fast-growing exotic tree species namely *Acacia mangium* (Schumach & Thonn.) Hook. f. and *Leucaena leucocephala* (Lam.) De Wit and one perennial, deciduous woody climber *Pueraria sp.* All three species have high relative abundance on all revegetated sites. The work of Osunkoya *et al*. (2005) showed that *Acacia mangium* (Schumach & Thonn.) Hook. f. has a high intraspecific competitive ability on disturbed land owing to high light intensities. High competitive advantage on disturbed lands due to ability to fix nitrogen (Guertin *et al*., 2008) applies to all three species. All three species are invasive species (Space *et al*., 2000; Buchanan, 2010; Guertin *et al*., 2008; Osunkoya *et al*., 2005) with high tendency to spread vigorously displacing indigenous plant species and forming monocultures, leading to "floral biodiversity *'thinning'* (Republic of Ghana, 2002).

In line with Collins (2005) that "invasibility correlates with propagule supply", *Leucaena leucocephala* (Lam.) De Wit and *Acacia mangium* (Schumach & Thonn.) Hook. f., produce profuse seeds spread by explosive mechanism. For example, *Acacia mangium* (Schumach & Thonn.) Hook. f. was not one of the tree species actively introduced on STSF-Bp; it got there by spreading from STSF-L. Such invasive behaviour tends to suppresses and excludes native plant pool, with the tendency to form monocultures (Collins, 2005); thereby impeding passive re-vegetation. It was observed during the survey that these species are rapidly colonizing STSF-L and STSF-Bp. The situation is lower in TMS possibly because the effect is not yet fully established as the site is only four years (compared to eight years for STSF-BP and STSF-L).

In the case of *Pueraria sp,* it smothers other plants that regenerate by passive revegetation, forming monoculture undergrowth. It also tends to engulf and eventually kill the tree species introduced by passive revegetation. At AGL, it is controlled by scalping (circle weeding) which when not done regularly affect growth and development of the tree species.

5.2.6 Species performance

Summation of relative abundance of species common to sites being compared showed differences in performance. For species common to all three re-vegetated sites, STSF-L ranked first followed by STSF-Bp and then TMS. However, comparison between STSFL and STSF-Bp shows that STSF-Bp was better than STSF-L. For species common to TMS and STSF-Bp, TMS was better than STSF-Bp whiles that for TMS and STSF-L showed STSF-L to be better than TMS.

Average plant height and girth at breast height of tree species actively introduced also indicated differences in performance. The average height of *Acacia mangium* (Schumach & Thonn.) Hook. f. was highest on TMS followed by STSF-Bp and least on STSF-L but for average girth at breast height (GBH) the trend is TMS followed by STSL and least in STSF-Bp. The average girth at breast height of *Acacia mangium* (Schumach & Thonn.) Hook. f. is TMS > STSF-L > STSF-Bp unlike the average height. *Leucaena leucocephala* (Lam.) De Wit has both average height and the average girth at breast height greater on STSF-L than TMS. Both the average height and the average girth at breast height for *Senna siamia* (Lam.) H. S. Irwin & Barneby are higher on TMS than STSF-L. For *Ceiba pentandra* (Linn.) Gaertn, average height is higher on TMS than STSF-L and same for average girth at breast height.

Total plant density is highest for STSF-Bp followed by STSF-L and least in TMS. The high total plant density of STSF-Bp is deceptive because many of the species recorded high frequencies in single quadrats. For example, *Diodia scandens* (Hiene & Sandwith) and *Lycopodium cernum* (fern) alone contributed to 48.6% of total plant density of STSF-BP. The densities are high because all life forms are included and that there was no cut-off diameter. The highest density for this study; 15,024 plants/ha (all life forms inclusive), compares with mean density of saplings only (15,043 individuals/ha) in Pappoe *et al*. (2010).

5.3 IMPACT OF REVEGETATION

5.3.1 Fauna Recolonization

The earthworm species collected were easy to characterize and count but were not very diverse, confirming what is stated in European Commission (2010). It was observed that earthworm diversity and population varied with percentage TOC, soil textural class, bulk density, level of compaction, amount of litter fall, degree of establishment of cover material and age of reclamation. The earthworm diversity and population size correlated positively with percentage TOC; best on RHR-F and least on STSF-Bp. This is in line with Wild (1988) that the organic matter level is an important factor in controlling the size of earthworm population. Considering *Eudrilus eugeniae* which was present in all sites, a correlation is observed between the population and textural class (Brady, 1996) of the upper 20cm from which they were sampled: RHR-F (loam) > STSF-L (silt loam) > TMS (loam) > STSF-Bp (clay loam). The poor level of earthworm population at STSF-Bp is attributable to the high level of compaction due to the clay type and possibly inadequate or no pulverization during soil preparation and non-replacement of topsoil.

At TMS the lower species diversity and lower population of *Benhania sp* compared to both the STSF-L and the control site is attributable to age of period of recolonization and the higher bulk density. It was observed that the use of *Pueraria sp* as groundcover in STSF-L and TMS provides a suitable habitat for a host of macro fauna (both above and below ground) compared to STSF-Bp where it is absent.

5.3.2 Soil Characteristics

5.3.2.1 Soil Physical Characteristics

5.3.2.1.1 Soil Moisture

Soil moisture content of the upper depths was generally higher than the lower depths. The moisture content of all the sites except TMS was good. Soil moisture is essential for nutrient movement in soil solution as well as maintaining a moderate soil temperature during hot days.

5.3.2.1.2 Bulk Density and porosity

The bulk density and porosity were negatively correlated; with the textural class of all sites being some form of loam, the porosity became a major determinant of bulk density. Bulk density ranged from approximately 1.0 to 1.5 g/cm^3 similar to the assertion by Houston *et al.,* 2002 that for most soils bulk density ranges from 1- 2 g/cm^3. The porosity and bulk density of TMS indicate a situation of compaction which explains the pockets of land without vegetation and stunted *Ceiba pentandra* (Plate 9) observed during the vegetation survey.

5.3.2.1.3 Saturated hydraulic conductivity (Ks)

The saturated hydraulic conductivity (Ks) for all revegetated sites were lower that the control site (RHR-F). With the highest proportion of silt and sand, STSF-L compared better to RHR-F. The low Ks value for TMS implies less storage during rainstorms. The low Ks value for TMS confirms the assertion in FAO (2000) that hydraulic conductivity is directly related to bulk density. The low Ks value has at least two implications for TMS: one, since runoff is the balance of rainfall volume and volume infiltrated and stored, coupled with the sharp slope at TMS, exceedingly high erosion rates is expected and this explains the struggle with erosion control at the site. Two, there is less water storage leading to situations where the vegetation is easily exposed to drought; as exemplified by withering of undergrowth at TMS (Plate 10) in just three weeks of no rain during the time of this study.

5.3.2.1.4 Soil texture

All sites exhibited some type of loamy texture. In terms of sand fraction domination, TMS compared well with RHR-F while STSF-L and STSF-Bp were more silt-fraction dominated. The silt loam texture of STSF-L at both depths is attributable to the accumulation of tailing decant whiles the facility was active. The texture of TMS being true loam provides more favorable conditions for plant growth and this explain the greater success of revegetation at the site.

5.3.2.2 Soil Chemical Characteristics

5.3.2.2.1 Soil Reaction

The pH level of the revegetated sites ranged from very acidic to alkaline whiles the undisturbed forest was very acidic. The pH levels of all the sites were outside the moderately acidic to neutral pH (5.5-7.0) which according to Sheoran *et al*. (2010), provides most satisfactory soil nutrient levels generally and hence optimal vegetation growth. The alkaline pH of STSF-L is attributable to the lime used in the raise the pH of process water decant prior to pumping to tailing storage facility. At RHR-F, converse to the expectation of a near-neutral pH, a very acidic pH and a corresponding high exchangeable acidity were recorded. This observation is possibly due to high leaching losses from the high precipitation experienced in the area.

5.3.2.2.2 Soil Nutrients

In contrast to the work by Yu *et al.*, (2010), levels of most nutrient elements are lower in shallower depths (0-20cm) than at the deeper depth (20-40cm) for all sites. This is possibly attributable to leaching (from region of elluviation; 0-20cm to region of illuviation; 20-40cm) as a result of 'the heavy and frequent rainfall experienced in the area.

5.3.2.2.3 Effective CEC

With reference to appendix II, Effective CEC is medium at only STSF-L but low for TMS, STSF-Bp and RHR-F. Since soils with a low CEC can only hold a small quantity of nutrients on the exchange sites so that the excess nutrients applied to the soil can easily be leached out by excess rain (FAO, 2000), the low CEC is a problem especially considering the regular and heavy rainfall regime of the area. To alleviate this problem, there is the need to improve soil organic matter content.

5.3.2.2.4 Exchangeable acidity and percentage base saturation

Since percentage base saturation indicates the tendency towards neutrality and alkalinity whiles exchangeable indicates the tendency towards acidity, the high percentage base saturation and the associated low exchangeable acidity is a good sign for improvement. Considering trend in CEC (Fig. 13), it is clear that there has been improvement compared to 2008 results indicating that soil systems are getting restored.

5.3.2.2.5 Total organic carbon (TOC) and Soil Organic Matter (SOM)

According to Ghosh *et al*., (1983) a total organic carbon greater than 0.75% indicates good fertility but for all sites, the percentage TOC was less than 0.75%. TOC level was best in the control forest followed by TMS then STSF-L and least in STSF-Bp. Similar to work by Maiti and Ghose (2005) TOC level correlated positively with available N and K. For all sites, the percentage organic matter was low; all revegetated sites had lower organic matter content than RHR-F but TMS did compare more to the control site. Since vegetation is already established with sufficient litter fall, providing sufficient conditions for earthworms will solve the problem of low organic matter content of soil.

5.3.2.2.6 Total Nitrogen and C:N ratio

For all sites, both total nitrogen and C:N ratio are low. C:N ratio, although low, proves the claim by Brady and Weill (1996) that the C:N ratio of the upper 15cm of arable soils commonly between 8:1 to 15:1 and lower for warmer regions and for subsoil. Since C:N ratio gives an indication of level of biological activities and is important in controlling the available nitrogen, effort to improve population of litter feeding organisms such as earthworms can improve the situation.

5.3.2.2.7 Heavy Metal Content

It was observed that on both STSF-L and STSF-Bp, with the exception of Hg, Se and As, with time, the levels of heavy metals in the topsoil, gradually decreased similar to work by Yu *et al.* (2010). This is possibly as a result of heavy metal accumulation in the cover crops and trees, volatilization and leaching from the high and frequent rainfall regime of the area.

5.4 COMPARISON OF THE EFFECTIVENESS OF REVEGETATION METHODS

The attributes of floral, faunal and soil characteristics give an integrated measure of how well the revegetation methods are doing and hence their effectiveness. Comparing all parameters measured (flora, fauna and soil) and taking into consideration the age of revegetation, it is clearly seen that the most effective revegetation method was the one at TMS followed by STSF-L and the least is STSF-Bp. The simplest explanation of this trend is the topsoil replacement; in the case of TMS, a two-layer topsoil was laid whereas on STSF-L and STSF-Bp, topsoil and compost were used only in holes for tree planting. The major factors responsible for the retarded progress of revegetation at STSF-Bp included planting holes dug in unpulverized clay subsoil and filled with topsoil prior to tree planting as well as non-establishment of cover plant layer.

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATION

6.1 CONCLUSION

When land is surface-mined, the entire forest, including shrub layer, tree canopy, root stocks, seed pools, animals, and microorganisms, are removed with its effect on soil fertility and productivity. However, if appropriate and effective methods are employed, land can be restored.

Revegetation methods and practices at Abosso Goldfields Limited was found not only follow the standard practices but also holistic and treats "causes" rather than "symptoms". The environmental management system comprehensively covers the anticipated disturbances with site-specific methods to establish sustainable projects. Revegetation at AGL starts right from the land disturbance stage ensuring only minimum but necessary impacts. Monitoring and maintenance is also extensive and corrective actions are taken without delay.

Adequate surface preparation to ensure sufficient quantity and quality of soil substrate is vital for revegetation success. Topsoil management and replacement is very vital in the recovery of disturbed lands and hence the effectiveness of revegetation method used. Comparing all parameters measured and taking into consideration the age of rehabilitation, the most effective revegetation method was that for TMS followed by STSF-L and the least is STSF-Bp. The reason behind the success of TMS, although two year younger that both STSF-L and STSF-Bp, is in the adequate topsoil quantity of topsoil in good quality returned in preparation for vegetation establishment. For revegetation of tailing storage facility, because the decant of tailings tend to produce sandy substrate, any attempt to increase topsoil return and heavy incorporation of organic matter will reduce the duration for successful rehabilitation.

6.2 RECOMMENDATION FOR REVEGETATION AT AGL

Subsoil pulverization and sufficient topsoil replacement should be ensured in the revegetation of Borrow pits since the development and establishment of vegetation of any plant community depends on the biological and the physico-chemical properties of the soil.

For revegetation at STSF-Bp to meet closure objectives, revegetation should be re-initiated ensuring that subsoil is pulverized, topsoil replaced cover material established prior to tree planting and drainage channel constructed

Owing to the problem of invasive species on forest integrity, the use of *Pueraria sp, Acacia mangium* (Schumach & Thonn.) Hook. f. *and Leucaena leucocephala* (Lam.) De Wit in revegetation should be limited to situations of extreme degradation. Alternative local species found to play their role in revegetation include *Centrosema pubescens* in place of *Pueraria sp* for cover material whiles *Anacardium occidentale, Casuarina equisetifolia, Gliricidia sepium and Musanga cecropioides in place of Acacia mangium* (Schumach & Thonn.) Hook. f. and *Leucaena leucocephala* (Lam.) De Wit.

6.3 RECOMMENDATION FOR FURTHER STUDY

Owing to the ability of *Pueraria sp, Acacia mangium* **(Schumach & Thonn.) Hook. f.** *and Gliricidia sepuim* to grow even under marginal conditions, the common trend is for mining companies to rely heavily on such species. These species, however, are problematic as invasive species and tend to smother local diversity to rather establish their monocultures.

I would therefore recommend that a study be conducted to investigate the extent of the problem of invasion by these species on revegetated areas.

Also, since earthworms as ecological engineers only indicate fauna return, I would recommend a further study which will survey fauna to give the complete inventory of returned fauna, their frequencies and relationship to the state of the restored vegetation.

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APPENDICES

APPENDIX I: GPS COORDINATES FOR STUDY SITES

STSF-L				**STSF-Bp**			
Locations	**N**	**W**	**Elev.**	**Locations**	**N**	**W**	**Elev.**
P1	05° 29.441'	001° 50.637'	125m	**P1**	05° 29.415'	001° 50.552'	120m
P2	05° 29.430'	001° 50.639'	122m	**P2**	05° 29.423'	001° 50.544'	115m
P3	05° 29.425'	001° 50.627'	126m	**P3**	05° 29.428'	001° 50.551'	119m
P4	05° 29.436'	001° 50.624'	123m	**P4**	05° 29.425'	001° 50.661'	113m
Plot 1	05° 29.436'	001° 50.634'	117m	**Plot 1**	05° 29.418'	001° 50.555'	117m
Plot 2	05° 29.439'	001° 50.626'	121m	**Plot 2**	05° 29.421'	001° 50.558'	115m
Plot 3	05° 29.436'	001° 50.629'	118m	**Plot 3**	05° 29.420'	001° 50.555'	121m
Plot 4	05° 29.429'	001° 50.623'	118m	**Plot 4**	05° 29.420'	001° 50.549'	125m
Plot 5	05° 29.434'	001° 50.637'	125m	**Plot 5**	05° 29.422'	001° 50.550'	126m
Plot 6	05° 29.434'	001° 50.631'	128m	**Plot 6**	05° 29.426'	001° 50.545'	122m
Plot 7	05° 29.430'	001° 50.627'	122m	**Plot 7**	05° 29.427'	001° 50.556'	129m
Plot 8	05° 29.425'	001° 50.627'	125m	**Plot 8**	05° 29.429'	001° 50.551'	120m
Plot 9	05° 29.427'	001° 50.630'	123m	**Plot 9**	05° 29.430'	001° 50.552'	124m
Plot 10	05° 29.429'	001° 50.634'	118m	**Plot 10**	05° 29.423'	001° 50.659'	122m

TMS				**RHR-F**			
Locations	**N**	**W**	**Elev.**	**Locations**	**N**	**W**	**Elev.**
P1	05° 29.13'	001° 52.176'	147m	**P1**	05° 26.568'	001° 54.139'	107m
P2	05° 29.002'	001° 52.1'70	145m	**P2**	05° 26.564'	001° 54.129'	111m
P3	05° 28.996'	001° 52.182'	149m	**P3**	05° 26.552'	001° 54.132'	113m
P4	05° 29.006'	001° 52.188'	151m	**P4**	05° 26.552'	001° 54.136'	114m
Plot 1	05° 29.008'	001° 52.175'	151m	**Plot 1**	05° 26.568'	001° 54.136'	110m
Plot 2	05° 29.003'	001° 52.172'	149m	**Plot 2**	05° 26.563'	001° 54.130'	115m
Plot 3	05° 29.005'	001° 52.176'	148m	**Plot 3**	05° 26.562'	001° 54.133'	119m
Plot 4	05° 29.001'	001° 52.175'	142m	**Plot 4**	05° 26.557'	001° 54.131'	110m
Plot 5	05° 29.008'	001° 52.182'	143m	**Plot 5**	05° 26.560'	001° 54.140'	105m
Plot 6	05° 29.005'	001° 52.180'	147m	**Plot 6**	05° 26.561'	001° 54.131'	129m
Plot 7	05° 28.999'	001° 52.180'	145m	**Plot 7**	05° 26.555'	001° 54.130'	118m
Plot 8	05° 29.004'	001° 52.185'	146m	**Plot 8**	05° 26.555'	001° 54.138'	108m
Plot 9	05° 29.000'	001° 52.183'	149m	**Plot 9**	05° 26.554'	001° 54.131'	101m
Plot 10	05° 28.998'	001° 52.183'	146m	**Plot 10**	05° 26.553'	001° 54.131'	110m

APPENDIX II: EARTHWORM SURVEY (RAW DATA)

	STFS-L		STFS-BP		TMS		RHR-F	
PLOT	**Q1**	**Q2**	**Q1**	**Q2**	**Q1**	**Q2**	**Q1**	**Q2**
1.2	4	4	0	0	1	0	2	1
1.4	7	7	0	1	1	3	3	1
2.3	4	4	0	0	0	0	3	3
2.5	9	0	0	0	3	0	1	0
3.1	9	5	0	0	1	0	2	1
3.3	3	1	0	0	0	0	3	8
4.5	2	5	0	0	0	2	1	0
5.2	0	6	0	0	0	0	0	2
5.4	4	2	0	0	0	0	3	4
5.5	4	4	0	0	0	0	0	3
TOTAL	**46**	**38**	**0**	**1**	**6**	**5**	**18**	**23**

APPENDIX III: SOIL CHARACTERISTICS INTERPRETATION KEY

Soil pH(1:1)	RANK/GRADE
<5.0	Very Acidic
5.0-5.4	Acidic
5.5-6.0	Moderately Acidic
6.1-6.4	Slightly Acidic
6.5-7.0	Neutral
7.1-7.4	Slightly Alkaline
7.5-8.5	Alkaline
>8.5	Very Alkaline

Organic Matter (%)	RANK/GRADE
<1.5	Low
1.6-3.0	Moderate
>3.0	High

ECEC(cmol(+)/Kg)	RANK/GRADE
<10	Low
10-20	Moderate
>20	High

BASE SATURATION (%)	FERTILITY RANK/GRADE
< 50	Low
50 – 70	Medium
70 – 90	High
> 90	Very high

Nitrogen (%)	RANK/GRADE
<0.1	Low
0.1-0.2	Moderate
>0.2	Adequate

Carbon/Nitrogen ratio(C/N)	RANK/GRADE
<13	Good Quality
13-20	Moderate Quality
>20	Poor Quality

Phosphorus, P (ppm) -Bray's No. 1	RANK/GRADE
<3	Very Low
3-10	Low
10-20	Moderate
>20	High

Potassium, K(ppm)	RANK/GRADE
<50	Low
50-100	Moderate
>100	High

Exch. Potassium [cmol(+)/Kg]	RANK/GRADE
<0.15	Low
0.15-0.25	Moderate
>0.25	High

Calcium, Ca(cmol(+)/Kg)	RANK/GRADE
<5	Low
5-10	Moderate
>10	High

Exch. Mg (cmol(+)/Kg)	RANK/GRADE
<1	Low
1.0 – 3.0	Moderate
>4.0	High

HEAVY METAL	NON-CONTAMINATED SOIL/ppm
Arsenic	3.0-12.0
Cadmium	0.1-1.0
Copper	1.0-5.0
Lead	10.0-70.0
Nickel	0.5-50.0
Selenium	0.1-4.0
Zinc	9.0-125
Iron	1.0-15.0
Manganese	1.0-50.0