

**The potentials of biological geotextiles in erosion control and of substrate amendment  
on vegetation establishment during gold-mine reclamation in Ghana**

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By

Master of Science

**Paul Kofi Nsiah**

from

**Offinso, Ashanti Region - Ghana**

Supervisor: Prof. Dr. rer. nat. habil. Wolfgang Schaaf

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## **Declaration**

I hereby declare that I have never had any permission to the final examination for a doctoral degree cancelled nor have I had a doctoral degree disqualified as a result of an attempt to deceive. I never made any attempt of deceit after the International PhD Programme ERM at the BTU Cottbus-Senftenberg.

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## **Dedication**

This thesis is dedicated to my wife and only girlfriend, Princess Mary Nsiah as well as our blessed children, Melody, Paul, Precious and Prince-Emmanuel for being by my side through the thick and thin.

Besides, the thesis is being dedicated to my late Christian parents, Mr. and Mrs. Owusu Banahene, for their support in my education and spiritual life. May your souls rest in perfect peace with the Eternal God Almighty!

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## Summary

Despite the significant contributions of the mining industry to the socio-economic growth and development of Ghana, mining operations have generated and continue to generate such severe adverse impacts on the environment that most Ghanaians perceive mineral discovery and subsequent mining as curse. Designing a comprehensive reclamation programme during the planning phase of a mining project, and implementing it concurrently throughout operations, has been shown to minimize environmental damage, reduce future clean-up costs and decrease potential legal liability. Although Regulation (23) of the Ghana Environmental Assessment Regulation (1999) requires mine proponents to have plans for reclamation, it has been revealed most degraded mine-sites have not been reclaimed. Even in cases where some mining companies made reclamation attempts, such efforts could not produce any favourable outcome due to the failure in adopting best reclamation management practices particularly (a) the stabilization of graded-slopes against soil erosion, (b) topsoil stockpiling and its subsequent application for future reclamation, and (c) the amendment of alternative materials for establishing vegetation in situations where it is difficult to obtain topsoil.

Subsequently, the main task of thesis was to help find solutions to the identified problems on mine reclamation by developing three broad goals to: (a) investigate the role of biological geotextiles in erosion and sediment control during reclamation; (b) examine the effects of organic amendments on stockpiled-topsoil as substrate for vegetation establishment; and (c) explore the feasibility of stockpiled-subsoil amendment with poultry manure as topsoil substitute for revegetation during reclamation of degraded mine-sites in Ghana. To achieve the broad goals, three kinds of field studies, each directed at one of the goals, were established at Newmont Ghana Gold Limited Ahafo-south project.

Soil erosion is a significant environmental impact of surface mining affecting the initial establishment of vegetation, especially on graded mine slopes. Hence, the first goal was pursued by establishing six experimental plots on a waste-rock dump at the Amoma Pit. Two kinds of biological geotextiles; Elephant-grass mat and “York” mat, were used with bare ground as control, in a randomized block design with two replications each. Data collected on sediment yield was expressed as a percentage from the mean total sediment yield. The results showed both the Elephant-grass mat and the York mat significantly ( $p < 0.05$ ) reduced soil loss by 56.6% and 97.3%, respectively, compared to the control. The mats acted as cover and protected the graded mine-slope against the erosive erosion and allowed vegetation establish and grow at the site.

Topsoil is a valuable resource and acknowledged as key component in successful revegetation of degraded mine-sites. It is, however, generally believed that stockpiling has detrimental impacts on soil properties and that stockpiled topsoil would require some organic amendments to promote plant growth. With this in mind, the second study tested the hypothesis that (a) topsoil stockpiling as practiced at Newmont has adverse impacts on soil properties and (b) amending stockpiled topsoil with organic materials, composted sewage sludge and poultry layer manure, promotes the survival and growth of planted trees. A separate portion of the waste-rock dump, measuring 36m by 45m, was covered with the stockpiled topsoil as the main

substrate for vegetation establishment. The stockpiled topsoil was assessed for physical and chemical properties and compared with fresh soil from a nearby un-mined site. The plot was randomly divided for the treatments poultry layer manure, composted sewage sludge, and no amendment (control). This was followed by planting equal number of potted-seedlings of five forest tree species and application of amendment materials on their respective plots. Diameter and height data of the planted trees and surviving numbers were collected seven and 14 months after planting. Statistical results, using the independent samples t-test, revealed stockpiling did not have any significant adverse impact on the measured soil properties. Similarly, one-way ANOVA combined with LSD and Duncan post-hoc tests ( $\alpha = 0.05$ ) indicated non-significant influence of the organic amendments on tree growth, compared with the control plot. The non-adverse impact of stockpiling on soil properties was chiefly ascribed to the topsoil management strategies implemented by the company during the stockpiling period that maintained good quality of the stockpile, that warranted no amendment. The principal driving factors that impeded tree growth and survival were observed to be that of competition from herbaceous plants due to the adopted revegetation approach and ineffective weed control.

Despite the significant contributions of topsoil in promoting vegetation establishment during reclamation, there exist some challenges on topsoil acquisition, for instance, unavailability at the mine-site, the topsoil being in deficit or contaminated with pathogens and invasive species. Hence, the third study was directed at the third goal by exploring the feasibility of stockpiled subsoil as topsoil substitute for establishing vegetation. The hypothesis was that amendment of stockpiled subsoil with poultry manure positively influences growth of trees and ground vegetation cover which promote better soil stabilization at degraded mine-sites. A different portion of the graded dump was covered with the subsoil. Two experimental plots ( $24 \times 15$  m) were established with the treatments poultry manure ( $23 \text{ t ha}^{-1}$ ) and control (no manure), followed by seeding of Cowpea (*Vigna unguiculata*) and planting of potted-seedlings of five forest-tree species. The Laser-point-quadrat method was used to estimate the ground vegetation cover, whereas erosion was visually observed. Diameter and height data of the planted trees and surviving numbers were collected. The results indicated the manure had significant positive influence on tree growth and on ground vegetation cover which facilitated superior soil stabilization, compared to the control. Characterization of the subsoil indicated lack of nitrogen (N) as the principal chemical limitation to vegetation growth. Therefore, addition of the poultry manure supplied sufficient N and additionally increased soil organic matter thereby promoting microbial activity and mineralization. This promoted significant tree growth as well as the establishment of a quicker and stronger ground vegetation cover that better protected the highly erodible subsoil against erosion and sedimentation.

The findings of the study highlight the urgent need of implementing best reclamation management practices in protecting the environment and securing successful reclamation during mine operations in Ghana. The achievement of this will promote responsible mining and further contribute to Ghanaians' acceptability of mining as a sustainable developmental land use activity, rather than as a curse.

Key words: Best reclamation management practices, composted sewage sludge, ecosystem restoration, land reclamation, mining operation, stockpiled topsoil, poultry manure, waste-rock dump, organic amendment.

## Zusammenfassung

Trotz der bedeutenden Beiträge der Bergbauindustrie zum sozioökonomischen Wachstum und zur Entwicklung Ghanas, hatten und haben Bergbauaktivitäten immer noch schwerwiegende negative Auswirkungen auf die Umwelt, wodurch die meisten Ghanaer die Exploration von Mineralien und den anschließenden Abbau als Fluch empfinden. Die Erstellung eines umfassenden Sanierungsprogramms während der Planungsphase eines Bergbauprojekts und dessen gleichzeitige Umsetzung während des gesamten Betriebs kann Umweltschäden minimieren, zukünftige Sanierungskosten reduzieren und mögliche rechtliche Verpflichtungen verringern. Obwohl die Verordnung (23) der ghanaischen Umweltprüfungsverordnung von 1999 vorschreibt, dass die Minenverantwortlichen Pläne für die Rekultivierung vorweisen müssen, wurde festgestellt, dass die meisten Minenstandorte nicht rekultiviert wurden. Selbst in Fällen, in denen einige Bergbauunternehmen Rekultivierungsversuche unternommen haben, konnten diese Bemühungen zu keinem positiven Ergebnis führen, da es nicht gelungen ist, die besten Rekultivierungsmanagementpraktiken anzuwenden, insbesondere (a) die Stabilisierung der steilen Halden gegen Bodenerosion, (b) die Lagerung von Oberböden und deren anschließende Verwendung für die Rekultivierung und (c) die Nutzung alternativer Materialien zur Etablierung von Vegetation in Fällen, in denen nicht ausreichend Oberbodenmaterial zur Verfügung steht.

Daher war die Hauptaufgabe dieser Arbeit, Lösungen für die identifizierten Probleme bei der Minenrekultivierung zu finden, indem drei allgemeine Ziele entwickelt wurden: (a) die Rolle biologischer Geotextilien bei der Erosions- und Sedimentkontrolle während der Rekultivierung zu untersuchen; (b) die Auswirkungen organischer Zusatzstoffe auf den Oberbodenmaterial als Substrat für die Begrünung zu untersuchen; und (c) den Einsatz Geflügelmist auf Unterbodenmaterial mit als Oberbodenersatz für die Rekultivierung degradierter Minenstandorte in Ghana zu untersuchen. Um diese Ziele zu erreichen, wurden im Ahafo-Süd-Projekt der Newmont Ghana Gold Limited (NGGL) drei Arten von Feldstudien durchgeführt, die jeweils auf eines der Ziele ausgerichtet waren.

Bodenerosion ist eine erhebliche Umweltauswirkung des Tagebaus, die insbesondere auf steilen Abraumhalden die anfängliche Vegetationsentwicklung beeinflusst. Daher wurde das erste Ziel verfolgt, indem sechs Versuchsfelder auf einer Abraumhalde der Amoma Pit angelegt wurden. Zwei Arten von Geotextilien, Elefantengras-Matten und "York"-Matten, wurden in einem randomisierten Blockdesign mit jeweils zwei Replikationen und unbedecktem Boden als Kontrolle angelegt. Die auf Basis der Sedimentausbeute gesammelten Daten wurden in Prozent der durchschnittlichen Gesamtsedimentausbeute der Kontrolle angegeben. Die Ergebnisse zeigen, dass beide Geotextilien den Bodenverlust im Vergleich zur Kontrolle um 56,6% bzw. 97,3% reduzieren konnten. Die Matten dienten als Abdeckung, schützten die steilen Halden vor Erosion und erlaubten die Ansiedlung sowie das Wachstum von Vegetation.

Oberboden ist eine wertvolle Ressource und gilt als Schlüsselkomponente für die erfolgreiche Wiederbegrünung degradierter Minenstandorte. Es wird jedoch allgemein angenommen, dass die Lagerung nachteilige Auswirkungen auf die Bodeneigenschaften hat und daher organische Zusätze zur Förderung des Pflanzenwachstums benötigt werden. Vor



diesem Hintergrund testete die zweite Studie die Hypothese, dass (a) die bei NGGL praktizierte Haldenbevorratung des Oberbodens negative Auswirkungen auf die Bodeneigenschaften hat und (b) die Melioration der Oberböden mit organischen Stoffen (kompostiertem Klärschlamm und Geflügelmist) das Überleben und Wachstum von gepflanzten Bäumen fördert. Eine 36 m x 45 m große Versuchsfläche wurde mit Oberbodenmaterial als Hauptsubstrat für die Vegetationsgründung abgedeckt. Das Material wurde auf seine physikalischen und chemischen Eigenschaften hin untersucht und mit gewachsenem Boden aus einem nahegelegenen, nicht bergbaulich genutzten Gebiet verglichen. Die Parzelle wurde zufällig für die Anwendungen Geflügelmist, Klärschlamm und Kontrolle unterteilt. Es folgte die gleichmäßige Pflanzung von Topf-Setzlingen von fünf Waldbaumarten und die Anwendung der organischen Zusatzstoffe auf den jeweiligen Parzellen. Durchmesser- und Höhendaten sowie Überlebensraten der gepflanzten Bäume wurden sieben und 14 Monate nach der Pflanzung erhoben. Die Ergebnisse zeigten, dass die Lagerung keine signifikanten negativen Auswirkungen auf die gemessenen Oberbodeneigenschaften hatte. Ebenso zeigte die einseitige ANOVA in Kombination mit LSD- und Duncan-Posthoc-Tests ( $\alpha = 0,05$ ) einen nicht signifikanten Einfluss der organischen Zusatzstoffe auf das Baumwachstum im Vergleich zum Kontrollplot. Die gute Qualität des Oberbodenmaterials wurde hauptsächlich auf die Managementstrategien von NGGL während der Lagerungsphase zurückgeführt. Die Hauptfaktoren, die das Wachstum und das Überleben der Bäume erschwerten, waren die Konkurrenz durch krautige Pflanzen aufgrund der angewandten Bepflanzungsmaßnahmen und der unzureichenden Unkrautbekämpfung.

Trotz der bedeutenden Beiträge des Oberbodens zur Förderung der Vegetationsentwicklung während der Rekultivierung gibt es einige Herausforderungen beim selektiven Gewinnung von Oberbodenmaterial, z.B. die unzureichende Verfügbarkeit am Minenstandort oder die Kontamination mit Krankheitserregern oder mit Samen invasiver Arten. Daher wurde in der dritten Studie untersucht, inwieweit auch Unterbodenmaterial als Oberbodenersatz für die Etablierung der Vegetation verwendet werden kann. Die Hypothese war, dass durch die Zugabe von Geflügelmist zu Unterbodenmaterial das Wachstum von Bäumen und die Vegetationsbedeckung positiv beeinflusst werden kann. Ein weiterer Teil der Halde wurde dazu mit Unterbodenmaterial abgedeckt. Zwei Versuchsfelder ( $24 \times 15$  m) wurden mit und ohne (Kontrolle) Geflügelmist ( $23 \text{ t ha}^{-1}$ ) angelegt, gefolgt von der Aussaat von Kuhbohnen (*Vigna unguiculata*) und der Pflanzung von fünf Waldbaumarten. Zur Schätzung des Deckungsgrades wurde die Laserpunkt-Quadrat-Methode verwendet, während die Erosion nur visuell erfasst wurde. Durchmesser- und Höhendaten sowie Überlebensraten der gepflanzten Bäume wurden erhoben. Die Ergebnisse zeigten, dass Geflügelmist einen signifikant positiven Einfluss auf das Baumwachstum und die Bodenbedeckung hatte, was im Vergleich zur Kontrolle eine bessere Bodenstabilisierung ermöglichte. Die Charakterisierung des Unterbodenmaterials zeigte einen Mangel an Stickstoff als wichtigste chemische Limitierung für das Vegetationswachstum. Die Zugabe von Geflügelmist führte zu einer Erhöhung der organischen Substanz der Stickstoffgehalte, wodurch die mikrobielle Aktivität und Mineralisierung gefördert wurde. Dies begünstigte ein signifikantes Baumwachstum sowie die Etablierung einer schnelleren und stärkeren Vegetationsbedeckung, die den hoch erodierbaren Untergrund besser vor Erosion schützte.

Die Ergebnisse der Studie zeigen, dass die Umsetzung verbesserter Rekultivierungsmanagementpraktiken zum Schutz der Umwelt und zur Sicherstellung einer

erfolgreichen Rekultivierung während des Minenbetriebs in Ghana dringend erforderlich ist. Die Erreichung dieses Ziels wird einen verantwortungsvollen Bergbau fördern und dazu beitragen, dass die Ghanaer den Bergbau als eine nachhaltige entwicklungsorientierte Landnutzung und nicht als Fluch akzeptieren.

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## List of abbreviations

AM	Amendment Material
ARA	Agronomy/Agricultural Reclamation Approach
ASAE	American Society of Agricultural Engineers
BGTs	Biological Geotextiles
BMPs	Best Management Practices
BRMPs	Best Reclamation Management Practices
BS	Base Saturation
BSS	Buck Scientific Spectrophotometer
CI	Conservation International
CSS	Composted Sewage Sludge
DOEC	Department of Environmental Conservation
ECD	Environmental Control Dam
ECEC	Effective Cation Exchange Capacity
EIA	Environmental Impact Assessment
EM	Elephant-grass Mat
EP	Elephant-grass Plant
FRA	Forestry Reclamation Approach
GCM	Ghana Chamber of Mines
GEAR	Ghana Environmental Assessment Regulation
GRA	Grassland Reclamation Approach
GVC	Ground Vegetation Cover
IFC	International Finance Corporation
MSRG	Mine Site Reclamation Guidelines
NAS	National Academy of Sciences
NGGL	Newmont Ghana Gold Limited
NRCS	Natural Resources Conservation Service
NSE	Nova Scotia Environment
OA	Organic Amendment
OC	Organic Carbon
ODOT	Oregon Department of Transportation
OM	Organic Matter
OMTs	Organic Materials

PLM	Poultry Layer Manure
PM	Poultry Manure
QLA	Quarry Life Award
REF	Reference Site
RSB	Reclamation Security Bond
SE	Saskatchewan Environment
SER	Society of Ecological Restoration
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
STP	Stockpiled Topsoil
STS	Stockpiled Subsoil
SY	Sediment Yield
TMS	Topsoil Management Strategy
UNEP	United Nations Environment Programme
UNGA	United Nation General Assembly
USDA	United States Department of Agriculture
WRD	Waste-Rock Dump
YM	York Mat

## CHAPTER ONE

### General introduction and study background

#### 1.1 Mining and its contributions to national economies

Mining is defined as the process of extracting minerals from the earth, which begins with the exploration for and the discovery of mineral deposits and continues through ore extraction and processing to the closure and remediation of worked-out sites (UNEP, 2000). Mining is mainly classified into two methods, surface and underground, depending on the depth of occurrence of the ore body. Surface mining is applied to ore deposits that lie near the earth surface usually by open pit excavations, whereas underground mining is the technique used for minerals lying deep beneath the surface. According to UNEP (2000) mining minerals are generally classified into four main groups: metals (e.g. gold, copper, silver, iron, aluminium, manganese); industrial minerals (such as lime or soda ash, asbestos, mica, potash, gypsum, salt), construction materials (sand, stone, limestone, gravel) and energy minerals (i.e. coal, natural gas, oil, etc.).

Mining is known to contribute significantly to the socio-economic growth and development of most economies, especially those in developing countries (UNGA, 2012). The Ghanaian economy, for instance, depends heavily on the mining of minerals such as gold, bauxite, diamond, manganese and recently oil, to derive the needed cash for her development. Ghana is the second largest gold producer in Africa, after South Africa and 10th largest globally. Besides, the country produces a number of industrial minerals such as kaolin, limestone, salt, sand and gravel, and silica sand on a lesser scale. The mining industry in Ghana is the leading export earner accounting for about 42% of the country's gross export revenue and 6.1% GDP in 2012 (GCM, 2014).

#### 1.2 Environmental impacts of surface mining

Surface mining operations involve the use of heavy equipment to remove the vegetative cover of the land and to strip the topsoil and the subsoils as well as the overburden in order to gain access to the ore materials (DOEC, 2005; CI, 2000; Larney and Angers, 2011; Zipper et al., 2011). Without proper management and regulations in place, these activities, along with construction of access roads and other ancillary facilities, can potentially result in severe disturbance or complete destruction of the soil and water resources, landscapes, vegetation, wildlife, fauna, habitats and air quality (DOEC, 2005, CI, 2000; UNEP, 2000; EIA Guide,

2010). For the purpose of convenience, the study has categorised the potential environmental impacts of mining under the following headings, which are followed by a detailed discussion of each:

- Effects on topography, topsoil, vegetation, fauna and habitat.
- Erosion and sedimentation.
- Acid mine drainage.
- Impacts of tailing impoundments, waste rock, heap leach, and dump leach facilities.
- Impacts of mine dewatering, and
- Impacts on air quality

### **1.2.1 Effects on topography, topsoil, vegetation, fauna and habitat**

Mining is basically about the extraction and further processing of minerals which directly aims at the removal of vegetation and topsoil (the main substrate for plant growth and development) as well as the displacement of fauna community following their habitat loss (UNEP, 2000). The massive removal of vegetation and topsoil generates bare surfaces whilst continuous stripping and dumping of overburden, waste and mineral rocks subsequently changes the topography or the landscape. Such changes could be seen as hills being modified to flat ground or depressions in the ground whereas valleys may be partially or completely filled with the overburden or waste rock to form flat or elevated ground with varying degrees of slope. Apart from the direct removal of topsoil, the dumping of huge volumes of the overburden and waste rocks also affect the topsoil at the neighbouring locations where the materials are being dumped or deposited (Darmody et al., 2009). The original topsoil at the dump site is covered by the transported materials, obscuring its surface from direct sunlight and precipitation. Furthermore, large pools of water impounded for dredging, as in placer mining, completely cover large volumes of topsoil. Excessive inundation of the soil definitely alters the nature of the soil, prevents oxygen and sunlight from reaching the soil, thereby eliminating its ability to support plant life.

### **2.2.2 Erosion and sedimentation**

Another significant environmental impact of mining is erosion and sedimentation. Soil erosion is the removal and subsequent loss of soil by the action of water, ice, wind, and gravity (ODOT 2005; Wright, 2000). Although soil erosion is a natural process, the process is exacerbated by highly disturbing anthropogenic activities such mining and construction (ODOT 2005; Risse and Faucette 2015; USDA, 2017; Wright 2000). Soil erosion by water

occurs in the following three mechanisms; particle detachment, sediment transport and sediment deposition. In the particle detachment phase, soil particles are detached from the parent soil mass by falling raindrops or by the shear forces of runoff (ODOT, 2005; USDA, 2017; Wright 2000). In the sediment transport phase, particles are moved down slope or carried in the runoff. The ability of the runoff to transport the detached particles is a function of the runoff velocity. The third phase, sedimentation, occurs when the velocity of the runoff is slowed and the load carrying capacity decreases, causing some or all the sediment to deposit. Generally, the larger, heavier particles deposit first and then the finer, smaller particles deposit further down slope.

There are five types of soil erosion caused by water namely, splash, sheet, rill, gully and stream or channel erosion (ODOT, 2005; Wright, 2000). Splash erosion results when the force of raindrops falling on bare or sparsely vegetated soil detaches soil particles that can easily be transported by runoff; whereas shallow sheets of water flowing over the soil surface generate sheet flow which transports soil particles that have been detached by splash erosion. If the process is not controlled, the surface flow changes from sheet to deeper concentrated flow along the low spots of the soil surface creating rivulets and cutting grooves called rills into the soil surface. Gullies are formed when runoff cuts rills deeper and wider or when the flows from several rills come together and form a large channel. Stream or channel erosion arises when stream bank vegetation is disturbed, or when the velocity or volume of a stream is increased thereby dislodging the soil particles.

The erosion potential for a given area is dependent on the complex interaction between soil type, topography, climate, soil cover, and management practices (Rickson, 2003; Wright, 2000; CI, 2000; Brady and Weil, 2008; Wischmeier and Smith, 1978). The Revised Universal Soil Loss Equation (RUSLE) illustrates how these characteristics interact to affect erosion rate and how each factor must be considered when planning for the stabilization of disturbed sites (Wischmeier and Smith 1978; Wright, 2000). The (R)USLE equation is:

$A = R \times K \times LS \times C \times P$ , where

- A = average annual soil loss in tons per acre per year.
- R = the rainfall erosivity factor or average annual total of storm energy by intensity.
- K = soil erodibility factor, which is measured or estimated for each soil and based upon soil properties (soil with a high percentage of silt is more erodible than clay).

- LS= hill slope length and gradient factor, which accounts for the effect of topography on erosion (increasing slope length and steepness will increase erosion).
- C = cover management, which represents the effect of vegetation, management, and erosion control practices (surface roughness will lower this factor).
- P = support practice factor, which is the ratio of soil loss with practices like concave slopes and contour ripping.

The RUSLE model shows that the length and steepness of a slope, combined with the soil type, precipitation and cover material, influence annual soil loss. Based on the RUSLE equation, mining activities including vegetation clearance, soil and overburden removal, creation of slopes, and subsequent exposure of the surface to the mercies of the atmospheric weather conditions, create a high risk for erosion and sedimentation. Unprotected construction and mining sites can have annual soil loss rates of more than 300 tons per acre (USDA, 2017; Wright, 2000). The problem becomes more threatening especially in tropical countries where rainfall intensities are extremely high. A study commissioned by the European Union (MINEO, 2000) summarises the phenomenon in the following manner:

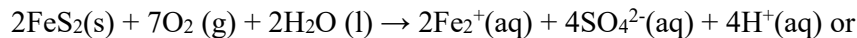
“Because of the large area of land disturbed by mining operations and the large quantities of earthen materials exposed at sites, erosion can be a major concern at hardrock mining sites. Consequently, erosion control must be considered from the beginning of operations through completion of reclamation”.

The study continues to mention potential causes of erosion and sedimentation at mine sites including open pit areas, heap and dump leaches, waste rock and overburden piles, tailings piles and dams, haul and access roads, ore stockpiles, vehicle and equipment maintenance areas, exploration areas, and reclamation areas. For most mining projects, the potential of soil and sediment eroding into surface waters and degrading it's quality is a serious problem. Apart from the potential for pollutant impacts on human and aquatic life, there are potential physical impacts associated with increased runoff velocities and volumes from disturbed land. resulting in downstream flooding, scouring of stream channels, and structural damage to bridge footings and culvert entries. Erosion removes the smaller and less dense constituents of topsoil (e.g. clay and silt particles and organic matter) that hold nutrients required by plants for healthy growth (Risse and Faucette 2015; Rickson 2006). The remaining subsoil is often hard, rocky,

infertile, and droughty; thus making re-establishment of vegetation difficult. Thus, the physical removal of soil particles as a result of erosion makes revegetation either naturally or with human assistance, extremely difficult, especially on slopes.

### 1.2.3 Acid mine drainage

Acid mine drainage or acid rock drainage refers to the production of acidic and metal-bearing solutions resulting from the oxidation of sulphide-bearing minerals (pyrites) through exposure to air and water (UNEP, 2000). Acid rock drainage occurs naturally within some environments as part of the rock weathering process but is exacerbated by large-scale earth disturbances characteristic of mining and other large construction activities. When the solid pyrite ( $\text{FeS}_2$ ) is exposed to oxygen ( $\text{O}_2$ ) and water ( $\text{H}_2\text{O}$ ), it is catalysed to form Iron (II) ( $\text{Fe}^{2+}$ ) ions, sulphate ions ( $\text{SO}_4^{2-}$ ), and hydrogen ions ( $\text{H}^+$ ). The hydrogen ions bind to the sulphate ions to produce sulphuric acid ( $\text{H}_2\text{SO}_4$ ) as shown in the equation below:



According to Earthworks (2010) many streams impacted by acid mine drainage can have a pH of 4 or lower and when the pH is raised past 3, either through contact with fresh water or neutralizing minerals, soluble Iron (II) ions hydrolyze to form Iron (III) hydroxide, a yellow-orange solid colloquially known as Yellow boy. Yellow boy discolours water and smothers plant and animal life on the streambed, disrupting stream ecosystems. In addition, the acid may leach or dissolve metals, metalloids and other contaminants from mined wastes and form a solution that is acidic, high in sulphate and elevated concentrations of cadmium, copper, lead, zinc, arsenic, etc. The metals often referred to as heavy-metals, with the potentials of contaminating streams and groundwater, can also enter and bio-accumulate up the food chain posing severe threat to human, plant and animal life in both terrestrial and aquatic ecosystems (UNEP, 2000). For example, in the Lusatian mining district of eastern Germany, Hüttl et al. (2014) report that recultivation efforts at many places were impeded by extreme ecological site conditions mainly due to the high pyrite content of the spoil material. Elevated levels of cyanide and nitrogen compounds (ammonia, nitrate, nitrite) can also be found in waters at mine sites, from heap leaching and blasting (EIA Guide, 2010).



#### **1.2.4 Impacts of tailing impoundments, waste rock, heap leach, and dump leach facilities**

Tailings, a by-product of metallic ore processing, is a high-volume waste that can contain harmful quantities of toxic substances, including arsenic, lead, cadmium, chromium, nickel, and cyanide, if cyanide leaching is used in ore processing (Wright, 2000). Aside the large stretches of land they cover, the impacts of tailings impoundments, waste rock, heap leach, and dump leach facilities on water quality can be severe. These impacts include contamination of groundwater beneath these facilities and surface waters. Toxic substances can leach from these facilities, percolate through the ground, and contaminate groundwater, especially if the bottoms of these facilities are not fitted with impermeable liners. Failure of tailings dams may release large quantities of toxic waters that can kill aquatic life and poison drinking water supplies for many miles downstream of the impoundment (EIA Guide, 2010).

#### **1.2.5 Impacts of mine dewatering**

Mining often progresses below the water table, so water must be constantly pumped out of the mine in order to prevent mine flooding. MINEO (2000) vividly describe an exclusive set of environmental impacts that result from the pumping and discharging mine water in the following manner:

“Mine water is produced when the water table is higher than the underground mine workings or the depth of an open pit surface mine. When this occurs, the water must be pumped out of the mine. Alternatively, water may be pumped from wells surrounding the mine to create a cone of depression in the ground water table, thereby reducing infiltration. When the mine is operational, mine water must be continually removed from the mine to facilitate the removal of the ore. However, once mining operations end, the removal and management of mine water often end, resulting in possible accumulation in rock fractures, shafts, tunnels, and open pits and uncontrolled releases to the environment”.

Ground water drawdown and associated impacts to surface waters and nearby wetlands can be a serious concern in some areas. Impacts from ground water drawdown may include reduction or elimination of surface water flows, degradation of surface water quality and beneficial uses, degradation of habitat (not only riparian zones, springs, and other wetland habitats, but also upland habitats such as greasewood as ground water levels decline below the deep root zone); reduced or eliminated production in domestic supply wells; water quality and

quantity problems associated with discharge of the pumped ground water back into surface waters downstream from the dewatered area (MINEO, 2000). Excavations from mining operation may lead to more rapid seepage into the groundwater, causing existing nearby streams or wells to be lost temporarily or permanently as shallow aquifers and water tables are drained off.

The problem of groundwater drawdown and associated impacts on surface waters was one of the main concerns of the Kenyase community during a public hearing on the commencement of underground mining operation of Newmont Ghana Gold Limited in the community. More so, underground mining may cause subsidence and induced fractures of the overlying strata that can cause streams to be diverted underground, drain shallow aquifers, or change the direction of groundwater flow. Besides, aquifers which are located below the mining level might be contaminated by poor quality mine water which might seep downwards.

#### **1.2.6 Impacts on air quality**

Large-scale mining has the potential to contribute significantly to air pollution, especially in the operation phase. All activities during ore extraction, processing, handling and transport depend on equipment, generators, processes, and materials that generate hazardous air pollutants such as particulate matter, heavy metals, carbon monoxide, sulphur dioxide, and nitrogen oxides. The largest sources of air pollution in mining operations are:

- Particulate matter transported by the wind as a result of excavations, blasting, transportation of materials, wind erosion (more frequent in open-pit mining), fugitive dust from tailings facilities, stockpiles, waste dumps, and haul roads. Exhaust emissions from mobile sources (cars, trucks, heavy equipment) raise these particulate levels; and
- Gas emissions from the combustion of fuels in stationary and mobile sources, explosions, and mineral processing.

Once pollutants enter the atmosphere, they undergo physical and chemical changes before reaching a receptor, causing serious effects to people's health and to the ecosystem.

#### **1.2.7 Noise and vibration**

According to EIA Guide (2010) noise pollution associated with mining may include noise from vehicle engines, loading and unloading of rock into steel dumpers, chutes, power generation, and other sources. Cumulative impacts of shovelling, ripping, drilling, blasting, transport, crushing, grinding, and stock-piling can significantly affect wildlife and nearby residents. While vibrations are associated with many types of equipment used in mining

operations, blasting is considered the major source. The various ways through which blasting can affect the environment can be seen in the form of fly-rock, ground vibrations, air blast, dust and gaseous fumes. Fly-rock has a high potential to cause damage such as shattering glass windows, making holes in roofs, injury and death to humans, and damage to plants and equipment. Vibration can affect the stability of infrastructures, buildings, and homes of people living near large-scale open-pit mining operations. Blasting noise and air shock can be troublesome if people live within close proximity to the blasting site.

No matter the scale of production (small or large), the potential environmental impacts discussed above can occur at all stages of the mineral development process (EIA Guide, 2010). While most impacts, for example pollution of rivers and streams from erosion and sedimentation, can be mitigated or offset by responsible mining through the adoption of best management practices (BMPs) (Norman et al., 1997), others such as habitat destruction resulting from vegetation and soil removal, can generally be mitigated through land reclamation (UNEP, 2000).

### **1.3 The concept of mine land reclamation and other related activities**

Mine land reclamation is a broad term and is often used in varied sense in the literature of after-use possibilities of a disturbed mine site. NSE (2009) describe mine reclamation as an integral part of the mineral development process, which is designed to restore to an acceptable state the physical, chemical, and biological quality of land and water regimes disturbed by mining activities. Various definitions of land reclamation including other related activities such as rehabilitation, restoration, revegetation, remediation, etc. have been given by different organizations, ecologist, restoration ecologist and scientific societies. Notable among them are highlighted below:

The National Academy of Sciences had defined reclamation in a report on rehabilitation potential of western coal lands (NAS, 1974) “as reconstructing a disturbed site to be habitable by the same organisms (or similar organisms in terms of ecological niche) present before disturbance in approximately the same composition and density”; and restoration “as returning a disturbed site to the exact condition it was in before disturbance”. Two decades later, Munshower (1994) on his part defined restoration as “return of a degraded site to the exact ecological condition it exhibited prior to disturbance”, and reclamation as “construction of topographic, soil and plant conditions which may not be identical to the pre-disturbance site, but which permits the degraded land to function adequately in the ecosystem of which it was and is a part”. Conservation International (2000) believes mine site reclamation is synonymous

with rehabilitation and defines the term as the restoration of mined land to its pre-mining conditions, or alteration to make it available for another productive use. On his part, Bradshaw (2002) mentions reclamation, rehabilitation, restoration and remediation, and further introduces an additional term; replacement. Bradshaw (2001) defines restoration as the return of an ecosystem to a close approximation of its condition prior to disturbance, in terms of both structure and function; whereas rehabilitation is used to indicate any act of improvement of the ecosystem from a degraded state.

On their part, MSRG (2007) explain reclamation as the process of returning a disturbed site to its natural state or one for other productive uses that prevents or minimizes any adverse effects on the environment or threats to human health and safety; and restoration as the renewing, repairing, cleaning-up, remediation or other management of soil, groundwater or sediment so that its functions and qualities are comparable to those of its original, unaltered state. The report continues to describe rehabilitation as activities undertaken to ensure that the mine land will be returned to a form and productivity in conformity with a prior land use plan, including a stable ecological state that does not contribute substantially to environmental deterioration and is consistent with surrounding aesthetic values; and remediation as the removal, reduction, or neutralization of substances, wastes or hazardous material from a site in order to prevent or minimize any adverse effects on the environment and public safety now or in the future.

With a more focus on the restoration of degraded ecosystems, the Society of Ecological Restoration (SER, 2004) defines ecological restoration as the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed. The society considers ecological restoration as one of several activities that strive to alter the biota and physical conditions at a site, and that some of these activities are often confused with restoration. Examples of the activities include reclamation, rehabilitation, revegetation, recultivation, mitigation, ecological engineering and various kinds of resource management, including wildlife, fisheries and range management, agroforestry, and forestry. According to the society, all of these activities can overlap with and may even qualify as ecological restoration if they satisfy all criteria expressed in the attributes of a restored ecosystem. The differences between the various terms are highlighted below.

The term reclamation is more applicable to disturbed mined lands or highly eroded soils and may encompass site stabilization using mechanical and/or temporary vegetation strategies as well as soil remediation measures to raise pH, add nutrients and modify bulk density (SER, 2004; Van Diggelen et al., 2001). On the other hand, the main goals of reclamation projects

include the stabilization of the terrain, assurance of public safety, aesthetic improvement, and usually a return of the land to what, within the stakeholders' interest, is considered to be a useful purpose (SER, 2004; CI, 2000; Wright, 2000). Rehabilitation is more related to forest ecosystems that have been degraded by factors such as fire, flooding, over exploitation of timber resources, etc., that leave intact physical soil properties and therefore do not require mechanical soil stabilization. Rehabilitation thus, emphasizes the reparation of ecosystem processes, productivity and services, whereas the goals of restoration also include the re-establishment of the pre-existing biotic integrity in terms of species composition and community structure (SER, 2004). This suggests the conversion of a natural tropical forest into artificial plantation forest can only be referred to as rehabilitation and not restoration since the achievement of pre-existing integrity in terms of species composition and community structure is not the immediate goal in such artificial plantation, although there is the reparation of ecosystem processes (energy capture, nutrient cycling, pollination), productivity (timber) and services. Even though rehabilitation would make the landscape more natural, it may not necessarily result in a significant increase of biodiversity (Van Diggelen et al., 2001). Hence, whereas the goal of reclamation may allow the conversion of an ecosystem into a different land use option, for instance, a forested land to agricultural or industrial site, after the mining activity, based on the agreed end land use by the various stakeholders, reclamation projects that are more ecologically based can qualify as rehabilitation or even restoration (SER, 2004). Revegetation is the process of vegetation establishment and aftercare undertaken as part of reclamation, rehabilitation or restoration, and may entail the establishment of only one or few species. Recultivation, on the other hand, generally applies to the agronomic and ecological aspects of reclamation, rehabilitation or restoration. However, the term recultivation is used in place of reclamation in Germany.

Remediation is the process of removing, reducing or neutralizing industrial soil, sediments and water contaminants that threaten human health and/or ecosystem productivity and integrity, mitigation is an action that is intended to compensate for an environmental damage. Mitigation is commonly required as a condition for the issuance of permits for private development and public works projects that cause damage to the environment. As have been discussed above, a good reclamation plan must propose mitigation measures in offsetting the potential impacts of such development activities. Then again, ecological engineering involves the manipulation of natural materials, living organisms and the physico-chemical environment to achieve specific human goals and solve technical problems. It thus differs from civil engineering, which relies on human-made materials such as steel and concrete.

#### **1.4 Mine reclamation plan as a means to guaranteeing responsible mining**

Designing a comprehensive reclamation programme during the planning phase of a mining project, and implementing it concurrently throughout operations, is required to minimize environmental damage, reduce future clean-up costs and decrease potential legal liability (CI, 2000). The Reclamation plan must conform to all phases of the mine development: exploration; feasibility, environmental assessment, construction and operation, and finally decommissioning and final reclamation (SE, 2008). Conservation International (2000) emphasizes that:

“Although reclamation is often viewed as something to be done after mining activity ends, reclamation techniques cover a wide range of activities that should begin in the earliest planning phases of a mining project. Mining companies should include reclamation plans in their initial production development reports as well as in their environmental impact assessments (EIAs). Mining companies should plan for and incorporate reclamation activities concurrently with the mining of the site, in order to reduce waste early on and prevent expensive clean-up after the site has been closed.”

EIA Guide (2010) also commands that “A mining project should not be approved unless the mining company has put forward a detailed, workable, and adequately funded plan to prevent environmental impacts for decades after mining ceases, and restore the ecology of the mine site as closely as possible to pre-mining conditions. It is also a prerequisite, during reclamation activities, for the companies to define and closely follow specific reclamation principles. These principles include the preparation of a reclamation plan prior to the commencement of operations, consultation with relevant stakeholders regarding the long-term, post-mining land-use objectives, and the adoption of progressive or concurrent reclamation strategy, right from the start of exploration through to the end of operations (Norman et al., 1997). Concurrent reclamation options are actions that are taken during mining operations before permanent closure (to take advantage of cost and operating efficiencies by using the resources available from mine operations), to reduce the overall reclamation costs. Progressive reclamation enhances environmental protection and shortens the time frame for achieving the reclamation goals and objectives, in addition to reducing the reclamation security bond (IFC, 2007).

Successfully achieving the approved post-mining land use(s) is the ultimate goal of any reclamation plan, therefore the post-mining land use will dictate the level of details required in the reclamation plan (Portle et al., 2002). At the end of mining activities, land reclamation measures are needed to restore the degraded sites to provide ecosystem services, such as wood production, atmospheric carbon sequestration, wildlife habitat, watershed protection (Skousen et al., 2011) or other land uses including agriculture and mine lakes (Hüttl and Weber, 2001). To be effective, communication must not only provide information on the predicted impacts of a project and the mine closure proposals and activities but also include listening to, and considering, public comments, concerns and feedback (SE, 2008). Therefore, whereas the overall goal of the reclamation plan is to produce a landscape that is safe, stable and compatible with the surrounding landscape and final land use, the specific objectives which are more or less site specific, should be practical, achievable and be prepared in conjunction with community inputs (NSE, 2009).

### **1.5 Topsoil management during mining operations**

Topsoil is generally defined as the A horizon of a soil which is usually darker and more fertile than the layer below (subsoil) because of the accumulation of organic matter (Rollett et al., 2015, Wright, 2000). Topsoil management (TSM) has been described as the salvaging, stockpiling and reapplication of topsoil or other selected materials to be used as growth medium in the reclamation of surface disturbance (NSE, 2009). Proper salvaging of topsoil during mining and its subsequent replacement in reclamation promotes successful vegetation establishment (Ferris 1996; Portle et al., 2002). Therefore, all available topsoil should be identified and salvaged from all areas that will be affected by mining activities such as excavation, filling, road construction or compaction by equipment and stockpiled (Ferris et al., 1996).

Whenever possible, the topsoil should be immediately replaced on an area where the landform reconstruction is complete, a strategy referred to as “direct return” (Wright, 2000). Direct return is extracting the topsoil from its place of origin and placing it directly onto an area that has already been mined, backfilled and graded for reclamation. It is the most desirable topsoil TSM option, as the topsoil is handled only once and does not compact during storage within stockpiles. Other advantages include avoidance of extra land for stockpiling, prevention of double handling, improvement of soil quality. In most cases, however, direct return is not feasible, especially at the beginning of mining operations, as there would be no ready sites to

be reclaimed. This then implies that topsoil must be salvaged and stockpiled for future reclamation.

Several studies have, however, demonstrated that stockpiling topsoil for long periods can affect the chemical, physical and biological properties of the soil (Abdul-Kareem and McRae, 1984; Mackenzie & Naeth, 2010; Stark and Redente, 1987; Wells and Potter, 1986). Therefore, appropriate measures need to be adopted to preserve topsoil quality during the period of stockpiling (SE, 2008). The stockpile locations should be selected to avoid slopes, natural drainage ways and traffic routes and where they will not be disturbed by future activities, as excessive handling will adversely affect soil quality (SE, 2008). The stockpile itself should be vegetated to protect it from erosion, discourage weeds, and maintain active populations of beneficial soil microbes

### **1.5.1 The need for topsoil substitutes during reclamation**

Even though, topsoil has been demonstrated to play a significant role in reclamation, there exist certain limitations on topsoil acquisition during mining operation. Some of these challenges include unavailability at mining site such as found at quarry sites (DOEC, 2005; Norman et al., 1997; Nsiah, 2012; Zipper et al., 2011). In other cases, though the topsoil exists, there are such challenges like contamination with plant pathogens and invasive weed seeds that render the topsoil unsuitable for restoration (DOEC, 2005; Wright, 2000). This suggests alternative materials must be used to substitute the topsoil in such cases. Topsoil substitute has been defined as any material, such as subsoil, overburden, waste rock, etc. applied as substrate for revegetation during reclamation (CI, 2000; Darmody et al., 2009; NSE, 2009). It is vital for the substitutes to meet certain chemical and physical criteria, such as ideal pH, texture and nutrients for vegetation growth (Skousen et al., 2011; Zipper et al., 2011). The topsoil substitutes may also need techniques or amendments to increase their organic matter and nutrient contents as well as to improve the physical properties for successful revegetation (Larney and Angers, 2012; Wright, 2000).

### **1.6 Organic amendments to improve soil quality**

Organic amendment (OMT) is a collective term used to describe materials rich in OM that are either a by-product of an existing process, such as biosolids (i.e. treated sewage sludge), or materials that have been produced as a result of some form of recycling process, such as compost (SNIFFER, 2010). Organic amendments contain useful quantities of major plant



nutrients (e.g. nitrogen, phosphate, potash, magnesium and sulphur), which are all essential for plant growth, and are also a valuable source of organic matter, which can improve soil physical, chemical and biological properties (Larney and Angers, 2012; Rollet et al., 2015; Wall, 2014). Thus, whereas that it could take 250 to 350 years for mine spoils to reach organic matter levels similar to adjacent undisturbed soils in Saskatchewan, United States the use of organic amendments in mine soil reclamation has been demonstrated to speed up the recovery process by injecting large amounts of organic matter to initiate nutrient cycling and overcome soil physical limitations (Anderson, 1977); Salazar et al., 2009; Shipitalo and Bonta, 2008).

Bending et al. (1999) maintain that SOM content, nutrient supply and pH are usually the most important determinants of the suitability of a disturbed site for restoration. Hence, it is important for the on-site mineral material to be analysed prior to the application of organic materials to provide guidance on appropriate organic material application rates to create a soil forming material (Rollet et al., 2015). Organic amendments affect soil properties in numerous and variable ways. Effects can be direct, through the intrinsic properties of the organic amendments themselves, or indirect, by modifying soil physical, biological and chemical properties. For example, the reclamation success of mine spoils with biosolids is due to at least three interrelated factors. Nitrogen is in a slow release organic form, rather than a readily available inorganic form which may be prone to leaching or runoff; high organic carbon content provides an instant energy source, which boosts soil microbial activity, and organic matter improves poor soil physical conditions resulting from topsoil loss and compaction.

In mine soil reclamation, vegetation establishment requires improvement of limiting conditions and re-initiation of carbon and nutrient cycling (Larney and Angers, 2012). Whereas chemical fertilizers add only nutrients, organic amendments have been shown to add both nutrients and organic matter, offering many more opportunities for improvement of soil physical, chemical and biological properties important for success of soil reclamation initiatives (Larney and Angers, 2012). The choice of amendment material (AMs) for use in reclamation is governed by various factors, ranging from the physical, chemical and biological suitability of the AM to those counterparts of the soil to the reclaimed, to potential for off-site movement of undesirable constituents; to material availability.

Even though application rates of OA of up to 100 tons per hectare have been recommended (SNIFFER 2010), the rates are site-specific based on the properties of the amendment materials (AMTs), such as C:N ratio, purpose of application and quality of in-situ material especially, pH, OM and nutrients, as well as the intended land use (Rollet et al., 2015). Most reclamation scenarios generally rely on a single activity with large amounts of organic

matter, rather than multiple lower amounts over longer time periods. The single activity ensures fast establishment of vegetation, which is crucial to initiation of nutrient cycling and improvement of soil physical properties. Mine soils tend to be subjected to the highest application rates of OAs because their high degradation state.

## **1.7 Erosion and sediment control in mine operation**

Effective erosion and sedimentation control requires first that the soil surface is protected from the erosive forces of wind, rain, and runoff, and second that eroded soil is captured on-site. Erosion control is the prevention or minimization of soil erosion whereas sediment control is the trapping of suspended soil particles (ODOT, 2005). Whereas erosion control is the preferred approach, sediment control is necessary because some erosion is unavoidable. Even though activities such as construction and mining may leave the land bare for a period of time, proper planning and use of erosion control measures can reduce the impact of man-induced accelerated erosion on such sites (ODOT, 2005). Combined with an understanding of basic erosion control and sedimentation processes, fundamental erosion prevention and sediment control principles will provide the groundwork for successfully implementing an erosion and sediment control plan.

### **1.7.1 Erosion prevention**

Protecting water quality and preventing erosion are two important tasks mine operators must address (Norman et al., 1997). Hence, the purpose of general site erosion control is to minimize erosion and limit the potential for sediment runoff into surface waters. It is important to plan ahead because erosion is often very difficult to control (with 100% accuracy) once it begins. Expensive solutions to water-quality problems can often be avoided by incorporating storm water and erosion control techniques into the mine development plan (Norman et al., 1997). Erosion prevention is the most effective and inexpensive method for reducing overall environmental impacts associated with mining and construction activities. Limiting the amount of exposed soil and directing surface water runoff away from exposed soil are two excellent ways to minimize erosion. Erosion control practices primarily involve preserving natural vegetation when possible or stabilizing exposed soils with temporary covers or permanent vegetation. With this in mind, timing, staging, minimizing the amount of exposed soil and directing surface water runoff away from exposed soil are all excellent ways to minimize erosion during mining activities.

An adequate vegetation cover is necessary to control erosion. However, revegetation takes time, and during that process landforms are susceptible to wind and water erosion. For the time between landform reshaping and planting of vegetation, erosion can be controlled by covering the soil with protective mulch or biological geotextiles, maintaining moisture in the soil, or erecting wind breaks to protect the landform from exposure to high winds (Hann and Morgan 2006; Rickson, 2006; Smets et al. 2007).

The following basic principles of erosion prevention and control can be adopted during mining and other earth disturbing activities (Portle et al., 2002; Wright, 2000):

- Keeping disturbed areas small and practical.
- Avoiding or minimizing the disturbance on highly erodible soils.
- Reducing exposure during expected wet seasons.
- Diverting runoff from the undisturbed area around the actively mined area to the extent possible.
- Stabilizing, vegetating, and protecting the site from raindrop and runoff as soon as practical.
- Grading all slopes to concave or complex slope shapes.
- Reducing slope lengths or gradients.
- Installing permanent and temporary sedimentation ponds and catchment basins.

The ultimate goal of any sediment control measure is to prevent erosion from starting. For example, vegetation establishment, is the most efficient way, or BMP to prevent or minimize erosion and is the ultimate goal of most sediment control measures. During active mining operations and until reclamation vegetation is established, additional measures are needed to prevent sediment from leaving the site. Sediment control BMPs must therefore be in place before land clearing and grading begins. The different BMPs which could be incorporated to control erosion and sedimentation at mine sites are described below.

### **1.7.2 Preservation of natural vegetation**

Maintaining natural vegetation is the most inexpensive form and best strategy in preventing erosion during mining and other the construction activities. Preserving natural vegetation in sensitive areas such as wetlands, stream corridors, lakes, and near steep slopes is particularly important in protecting the ecosystem during mine operations. Vegetation is the most effective means of stabilizing soils and controlling erosion. It shields the surface from the impact of falling rain, reduces flow velocity, and disperses flow. Vegetation provides a rough

surface that slows the runoff velocity and promotes infiltration and deposition of sediment. Plants remove water from the soil and thus increase the soil's capacity to absorb water. Plant leaves and stems protect the soil surface from the impact of raindrops, and the roots help maintain the soil structure while holding the soil in place (ODOT, 2005).

### **1.7.3. Vegetative filters and grass-lined swale**

Vegetative filters are grassy areas, which act as sediment filters. The coarser particles settle as the flow decreases in velocity. The finer particles settle in the lower portion of the filter. Vegetative filters function properly only when flows are not concentrated and in areas of low sediment yield. Grass-lined wale is channel with vegetative lining constructed to convey and dispose of concentrated surface runoff without damage from erosion, deposition, or flooding (ODO, 2005).

### **1.7.4 Silt fence**

A silt fence is a barrier of geotextile fabric, or filter cloth, used to temporarily intercept sediment-laden runoff from small drainage areas (Wright, 2000). A silt fence can be used to control sheet flow, reduce runoff velocity, and help retain transported sediment on the site, thus reducing erosion and enhancing water quality. Silt fence is commonly placed at the bottom of a disturbed slope or adjacent to streams and ponds.

### **1.7.5 Sediment barriers**

Sediment barriers can be constructed from a variety of materials. Examples include:

- Berm (filter berm): a constructed barrier of compacted earth or entrenched aggregate.
- Sand bags: bags manufactured from durable, weather resistant tightly woven material filled with sand or gravel.

### **1.7.6 Outlet protection**

This involves the use of an energy-dissipating device at the outlet of a pipe or conduit to prevent excessive erosion and scour. It includes riprap-lined basins, concrete aprons, and settling basins. Outlet protection prevents scour at storm water outlets, and minimizes the potential for downstream erosion (ODOT, 2005).

### **1.7.7 Inlet protection**

Prevents coarse sediment from entering storm drainage systems by filtering runoff and retaining sediment before it reaches a drainage inlet or storm sewer system. This practice helps

to keep the conveyance channel free from debris or sedimentation that could reduce the capacity of the channel (ODOT, 2005).

#### **1.7.8 (Rock) Check Dam**

A check dam is a small barrier constructed in a drainage way to reduce channel erosion by reducing the flow velocity. Check dams are appropriate for use in small drainage, but are not for use in perennial streams.

#### **1.7.9 Temporary slope drain**

A temporary slope drain is a pipe that extends from the top to the bottom of a cut or fill slope to convey high concentrated runoff (water) without causing erosion (ODOT, 2005). They are used in conjunction with berms along the edges of newly constructed slopes until permanent storm water drainage structures are installed or until vegetation has adequately stabilized the slope, where they are then removed (Wright, 2000).

#### **1.7.10 Temporary diversions (diversion dike)**

A temporary diversion is a berm or swale used to prevent sediment-laden waters from leaving a site and to prevent offsite or upstream waters from entering a site. Diversions are also used to direct the sediment-laden water to a specific control such as a sediment pond. Typical diversions are combinations of berms and ditches and are temporary structures. Temporary diversions used in final reclamation should be removed after vegetation has stabilized the site (ODOT, 2005; Wright, 2000).

#### **1.7.11 Sedimentation pond (environmental control dam)**

Once soil erosion occurs, sediment trapping or removal techniques can reduce the amount of sediment and associated pollutants that leave the site, thus protecting nearby streams, wetlands, and lakes. Sedimentation pond or environmental control dam (ECD) are usually placed around the perimeter of a disturbed area and where concentrated water leaves the site. They may be excavated or constructed with an embankment of earthen materials to retain water and/or slow the velocity so that sediment can settle to the bottom of the structure (ODOT, Wright, 2000).

#### **1.7.12 Spillway**

There is the need to consider the potential for outflow from a sedimentation pond. Even a pond sized for total containment for the maximum probable precipitation event should consider where water will flow if the pond is overtopped. A spillway is a designed structure provided to control the outflow from a pond and to safely convey the water in a manner that

minimizes erosion and protects the structure. There are two types of spillways, emergency and primary. The emergency spillway is typically a broad-crested weir that moves from a low slope to a steepened slope. The point of slope break is called the control. The emergency spillway serves to protect the structure and control the flow when the pond discharges and when the primary spillway cannot handle the flow volume. A primary spillway is generally used for more frequent discharges and is often a trickle tube or drop inlet for sedimentation pond designs. The primary spillway helps control the outflow rate and detention time of a sedimentation pond. A decant enables the spillway to empty the pond for sediment clean-out and to maintain the detention time between storms that occur in close sequence.

#### **1.7.13 Surface roughening**

Leaving the slopes in a roughened condition after clearing or creating a rough soil surface with horizontal depressions or grooves will trap seed and reduce runoff velocity. Roughening can be accomplished by 'track walking' slopes with tracked equipment, by using a serrated wing blade attached to the side of a bulldozer, or by other agricultural equipment such as spike-toothed harrows.

#### **1.7.14 Erosion control matting (biological geotextiles)**

The Society for Engineering in Agricultural, Food, and Biological Systems (ASAE, 1992) defines geotextile as a "fabric or synthetic material placed between the soil and a pipe, gabion, or retaining wall: to enhance water movement and retard soil movement, and as a blanket to add reinforcement and separation." There are two types of geotextiles; natural and man-made, depending on the material from which it is made. Geotextiles produced from man-made materials such as nylon, polypropylene, polyester, polyethylene etc., are referred to as synthetic geotextiles, whereas, those manufactured from natural materials (plants) like jute, coir, sisal, cereal straw and palm leaves are referred to as biological or biodegradable geotextiles, due to their general ability to undergo complete decomposition (Rickson, 2006). Newly reclaimed sites may suffer from over-steepened slopes, exposure of highly erodible soils, and lack of vegetation cover, contributing to high erosion risk. Vegetation can significantly reduce soil erosion rates compared to un-vegetated sites, but establishing an effective vegetation cover may take several seasons (Rickson, 2003; Wright, 2000). Biological geotextiles can serve as temporary replacement of the vegetative cover to protect the soil against erosion until permanent vegetation is established (Hann and Morgan, 2006; Smets et al., 2007). Geotextiles begin to control soil erosion immediately after installation. Effective geotextiles mimic the erosion-control properties of vegetation (% cover of the soil surface,

roughness imparted to flow, water retention and improved soil infiltration). The basic objective of erosion-control matting is to provide a stable seedbed for one or more growing seasons until vegetation establishment (Wright, 2000). Erosion-control matting disperses raindrop impact, then biodegrades and disappears as vegetation is established (Rickson, 2006; Wright 2000).

#### **1.7.15 Cover crop of vegetation**

Grasses and legumes may be selected to provide initial quick cover for erosion and sediment control (NSE, 2009).

#### **1.7.16 Dust control**

Preventative measures to minimize wind transport of soil, prevent traffic hazards and reduce sediment transported by wind and deposited in water resources. Dust control is usually applicable on construction routes and other disturbed areas subject to surface dust movement and where off-site damage may occur if dust is not controlled (ODO, 2005).

### **1.8 Stages in mine-site reclamation**

Reclaiming degraded mine-sites (such as waste-rock dumps, tailings dams, etc. may encompass the following five stages: (i) site grading and re-shaping (landscape design), (ii) placement of available substrate and necessary amendments; (iii) site stabilization (erosion and sediment control measures), (iv) revegetation, and (v) monitoring and maintenance (Naeth et al., 2013)

#### **1.8.1 Landscape design**

Landscape design or re-shaping of landform by grading the site to a pre-designed plan is an essential component of the reclamation process (NSE 2009, CI, 2000). Earthwork and grading (or land shaping) in the reclamation phase of mining must take into account that the land will have been disturbed twice, once in the mining phase and again in the reclamation phase (Wright, 2000). Minimizing the amount of land excavation and alteration during mining operation yields a cost benefit as well as lessening the impact to the environment. Earthwork (backfilling and grading) accounts for up to 90% of reclamation costs (Wright, 2000). Top concerns during earthwork and grading are safety and erosion. Good mine planning and design can reduce the amount of re-shaping of waste or overburden piles that is required during or after completion of mining. The final land form must be stable and hydrologically compatible with the surrounding area (NSE, 2009). A description of the proposed earthwork and reclamation, including final slope angles, high wall reduction, benching, terracing and other

structural slope stabilization measures should be available. It is generally required the site be contoured to mimic the local topography and blend into surrounding landscape consistent with future land use or land cover.

### **1.8.2 Placement of available substrate**

One of the most important components of a successful reclamation programme is to have a suitable substrate for establishing the vegetation. Ideally it is best to use the original topsoil from the disturbed area. In most situations, the topsoil from all areas being cleared should be retained for subsequent reclamation. The topsoil contains the majority of seeds and other plant propagules (such as rhizomes, roots, etc.), soil micro-organisms, organic matter, and the more labile (more readily cycled) plant nutrients. Sufficient depth of substrate must be replaced to maintain adequate root growth and nutrient requirements.

The substrate is required to be characterised for such properties as texture, bulk density, pH, moisture regime, nutrients and organic matter as well as potential contaminants. Any necessary amendments and/or remediation must be undertaken to enhance the reclamation success (SNIFFER, 2010). Soil preparation may include the addition of chemical fertilizers, or organic amendments such as composted sewage sludge and/or mulches, manure, etc. Native plants are likely to require fewer nutrients in comparison to agricultural plants therefore application rates should be examined on test plots before general application (Wright, 2000).

### **1.8.3 Site stabilization (erosion and sediment control measures)**

A major environmental concern, which runs through all stages of the mine development process is erosion and sedimentation following the soil disturbing activities. The problem becomes unusually pertinent, especially in tropical climates like Ghana where rainfall intensity is very high. The necessary measures on erosion and sediment control during mine operations have been described in the previous section (1.7)

### **1.8.4 Revegetation**

Having temporary stabilized the newly reclaimed site through the installation of biological geotextiles and other erosion control BMPs, the next stage is to permanently protect the site through revegetation. Revegetation is thus, one of the final reclamation steps that is essential for effective and successful reclamation. Planning revegetation requires a knowledge of the pre-existing conditions and a vision for the long term integrity of the ecosystem that remains after mining is completed. The selection of species for revegetation generally depends



on the future land use, soil conditions and climate of the mining area (NSE, 2009; Wright, 2002).

The goal of restoring most tropical forest ecosystems is generally to develop an ecosystem that will move through the stages of ecological succession and facilitate the accumulation of biomass (CI, 2000). Therefore, native pioneer species which are usually light tolerant, low energy demanding and can withstand the initial harsh site conditions can be used to condition the soil and provide a more appropriate habitat conditions (in terms of shade, humidity, low temperatures) for the later stage of high energy-demanding plant species. In certain situations, however, the adoption of successional reclamation, which is a multi-staged process that relies on different treatments over a period of time by initially selecting non-native species to serve as colonizers which will be later succeeded by native species, is very necessary (NSE, 2009). This cover may be important as a bridge between initial colonizers and later developing native vegetation.

It is always prudent to save some pockets of the original vegetation during mining especially in the tropics, as such small pockets of tropical forest to form centers of colonization, thus serving as a source of bacteria, fungi, seeds and plants that will promote the generation of the natural ecosystem and reduce the cost of closure (CI, 2000). Besides suitable substrate, adequate moisture is a critical element for revegetation success. Therefore, seeding should take place immediately before rains begin or early on in the rainy season (Wright, 2000). Fertilizer (both organic and inorganic) may be used to speed up natural processes by increasing species number, plant cover and density, and growth rates (CI, 2000).

### **1.8.5 Monitoring and maintenance**

Invasion by animals, weeds and human activities can thwart reclamation efforts. Maintenance of the area being reclaimed is necessary to predict and address these problems. Because achieving a self-sustaining ecosystem may take years, maintenance and monitoring for several years is especially important. Companies should be prepared to rework areas that are not developing adequately. Maintenance might include replanting failed areas, repairing erosion problems, implementing fire management systems, controlling pests, weeds and animal populations, using fertilizer (chemical or organic), and applying lime to control pH (CI, 2000).

According to NSE (2009) the reclamation monitoring programme may involve the following activities:

- monitor progress of revegetated areas following initial planting until vegetation is successfully established,

- regularly conduct soil analyses for nutrients and pH until vegetation is demonstrated to be successfully established,
- take corrective action in areas showing evidence of erosion, sedimentation or slope failure,
- take appropriate measures to address evidence of excessive vegetation stress, invasive species or poorly established areas.

## **1.9 Determination of revegetation success and retrieval of financial assurance**

### **1.9.1 Revegetation success standards/criteria**

One of the most important requirements of a successful reclamation plan is the identification of methods to be applied in determining when revegetation and reclamation can be deemed complete. Thus, there must be reclamation and revegetation success criteria which provide a reference point to evaluate the success or otherwise of the revegetation and the entire reclamation, in an objective manner, in order to allow for any bond release. These criteria are essential for judging, by both the regulatory authority and the mine proponent, when the end point of the reclamation period has been reached. The appropriate success criteria will be dictated by both specific site conditions and post-mining land use of the area (Portle et al., 2002). Potential techniques that may be applied to determine if compliance with the revegetation success standards and subsequent reclamation are met include the estimation of vegetation cover, plant density and/or diversity, and other applicable measures.

Sufficient vegetation cover may be achieved by comparing recently revegetated areas (reclaimed) to either some reference area that represents an older, stabilized reclaimed site, an un-mined nearby area; or a collected baseline data on the vegetative cover (i.e. density, diversity, percent cover) that existed prior to mining and compare it to the reclaimed, revegetated areas. Another alternative is to compare the density, diversity and percent cover of the reclaimed area to an approved alternate technical standard contained in an accepted reference publication, for example from the regulating agency. Since a primary objective of revegetation is to stabilize the site, it is important to provide high degree of vegetative cover, as quickly as possible, in protecting the soil from the effects of raindrop impacts which will be absorbed by the vegetative canopy. This protection translates into reduced erosion and sedimentation and subsequent site stabilization. The survival and growth rate of certain planted species per unit area (ha) may also be used especially where the end land use is to establish forest ecosystem.

### **1.9.2 Diversity**

Diversity is important in establishing long-term stability in the plant community. It also helps to ensure that the plant community is not susceptible to being taken over by weeds during times of stress. Such stability is especially important in withstanding stress such as climatically unfavourable or extreme years, disease, pest infestation, disturbance from grazing, wildlife utilization, insect infestation, fire, drought or windfall. The method of measuring diversity should be included in the reclamation plan and based upon appropriate scientific methodology (Portle et al., 2002).

### **1.9.3 Reclamation security bond (financial assurance)**

It is a requirement for the mine proponent to post a reclamation security bond (RSB), upon approval of the reclamation plan and prior to the initiation of mining, to guarantee that the regulatory authority has access to enough funds to perform the site reclamation should the proponent fail to reclaim the site. Once the reclamation is complete and certified by the regulatory agency, the financial assurance funds is released back to the operator. This amount must equal as closely as possible the cost to the regulatory authority of hiring a contractor to complete reclamation. That is to say the financial assurance must reflect the cost of hiring an outside contractor to do the work, and not the cost to the operator if they performed the work themselves. Where the reclamation plan calls for conducting the reclamation in phases, the cost should be broken down according to the phases, which would allow for bond release upon successful completion of each phase.

### **1.9.4 Criteria for releasing financial assurance**

The RSB is to be released upon an approval by the regulatory authority that the specific criteria for measuring the success of site reclamation have been met by the proponent. The success criteria should involve specific, quantifiable measures that are proposed in the reclamation plan by the operator and approved by the regulatory authority prior to mine operations. Thus, there must be a well-defined and objective method for the regulatory authority to evaluate the reclaimed site and assess the success of reclamation. This evaluation serves as the basis for the determination that final reclamation of the mining site has been achieved. The financial assurance for a particular site must be released to the proponent, after the regulatory authority has issued a certificate of completion, which shows that particular site has been successfully reclaimed.

Success criteria for performance should be defined and agreed on by consulting with all relevant parties. Components of such criteria include physical criteria such as stability,

resistance to erosion, and re-establishment of drainage; biological criteria including species diversity, canopy cover, seed production, and weed control; water quality standards for drainage water; public safety; productivity of food crops; and the development of a sustainable forest management program.

### **1.10 Problem statement**

Despite the significant contributions of mining to the socio-economic growth and development of Ghana (GCM, 2014) mining operations have generated and continue to generate severe adverse impacts on the environment (Nsiah, 2008; 2012). More importantly, in Africa and Ghana in particular, most of these mining activities occur in communities that depend heavily on the land for agriculture and forestry. The resultant effect is that several hectares of both forested ecosystems and arable lands are left in deplorable conditions unable to support neither the growth of the original vegetation that existed before the mining took place nor any food crops, thereby jeopardizing the livelihoods of the communities. Due to the negative impacts being realised from mining activities, most Ghanaians perceive the discovery of minerals and subsequent mining as a curse in a country that was called Gold Coast by her colonial masters because of her endowment with abundance of gold and other mineral resources. The truth, however, is that mining serves as the foundation for the sustenance and development of man offering the opportunity to catalyse broad-based economic development, reduce poverty, and assist countries in meeting internationally agreed development goals, including the Millennium Development Goals, when managed effectively and properly (UNGA, 2012).

Having acknowledged the importance and benefits of mining to the socio-economic growth and development of man, the question arises as to how can mining be managed effectively and properly as promulgated by UNGA (2012)? Or better still, how can mining be conducted to achieve the full economic and social benefits and also ensure the environmental benefits are not relegated? A plausible answer to these questions is that mine proponents must have plans for reclamation prior to the onset of mine operation (NSE 2009; SE 2008; EIA Guide 2010). Mine land reclamation is defined as either the restoration of mined land to its pre-mining conditions, or alteration to make it available for another productive use (Conservation International 2000). Designing a comprehensive reclamation program during the planning phase of a mining project, and implementing it concurrently throughout operations, has been shown to minimize environmental damage, reduce future clean-up costs and decrease potential legal liability (CI, 2000).

Mine land reclamation in Ghana was not mandatory until the enactment of the Environmental Assessment Regulation 1999, (L.I. 1652), a Regulation that gives details on the processes of conducting Environmental Impact Assessment (EIA). Regulation (23) requires large-scale mine proponents to have plans for reclamation and to also post a Reclamation Security Bond to be used to reclaim the disturbed lands by a third party in case the company fails to reclaim the site. However, personal field observations and studies have revealed most disturbed mine sites in Ghana have not been reclaimed (Nsiah, 2008; Nsiah, 2012). Even in cases where mining companies made reclamation attempts, such efforts could not produce any favourable outcome due to the failure in adopting best reclamation management practices (BRMPs). As shown in Fig. 1.1 and 1.2, notable among the failures included (a) stabilization of slopes against erosion and sedimentation during the initial stages of revegetating the disturbed mine sites (b) topsoil stockpiling and its usage as substrate for revegetation; and (c) the amendment of alternative materials for establishing vegetation in situations where it is difficult to obtain topsoil.



Figure 1. 1: A “reclaimed” mine site in Ghana without slope stabilization, topsoil application or amendment of applied substrate.



Figure 1. 2: A “reclaimed” mine site in Ghana without slope stabilization, topsoil application or amendment of applied substrate.

Moreover, in Ghana, there exist large stretches of degraded and abandoned lands, caused by the so-called “legal” and illegal mining popularly referred to as “galamsey” (gather the minerals and sell), where the topsoils were not stockpiled at the time of the mining operations (Fig. 1.3).



Figure 1. 3: A degraded and abandoned mine-site in Ghana

The abandoned mine-sites pose serious ecological and safety risks and also serve as continuous sources of pollution to rivers and streams (Fig 1.4).



Figure 1. 4: Environmental pollution and safety risks of Galamsey mining in Ghana

All such degraded sites must therefore be reclaimed to eliminate the risks and to make those lands available for productive uses. Importing topsoil from undisturbed areas in reclaiming those degraded and abandoned mine-sites is a potential option. However, such a practice has been associated with other challenges such as high transportation costs, whereas the topsoil exporting area is degraded to fix a problem elsewhere (Darmody et al., 2009; Larney & Angers, 2012). Therefore, alternative sources of growth media or topsoil substitutes must be created to ensure successful reclamation of the sites.

The above problems on mine reclamation in Ghana are seen as threats to achieving the overall goal of reclaiming disturbed mine sites to make them safe, stable and compatible with the surrounding landscape and end land-use. Hence, the urgent need to implement sustainable land reclamation measures in protecting the environment and restoring the degraded sites to productive use. The solutions to the problems are perceived to contribute significantly to the successful reclamation of disturbed mine lands in Ghana which will in turn promote public acceptability of mining as a developmental land use activity, rather than as a curse.

### 1.11 Study aim, hypotheses and objectives

The main aim of this thesis was to undertake a comprehensive field study and come out with feasible and practical interventions in prevailing over the identified problems and promote successful mine land reclamation in Ghana. With this in mind, three broad goals were pursued to:

1. Investigate the role of biological geotextiles in erosion and sediment control during reclamation of disturbed mine-sites.
2. Evaluate the effects of organic amendments on topsoil stockpile as substrate for vegetation establishment.
3. Explore the feasibility of stockpiled subsoil amendment with poultry manure as a potential topsoil substitute for revegetation during mine-site reclamation.

Three kinds of field experimentations, each directed at achieving one of the above goals, were conducted at an active surface gold mine-site of Newmont Ghana Gold Limited Ahafo-south project, in the Brong-Ahafo Region.

The first study focused on the utilization of two kinds of biological geotextiles (BGTs) constructed from two local plants; the Elephant grass plant (EP) (*Pennisetum purpureum*) and the paper mulberry plant (*Broussonetia papyrifera*) to control erosion and sedimentation at the mine. The specific objectives were to:

1. design and construct BGTs from the EP using an appropriate technology;
2. evaluate the performance of EM and that of YM BGTs in reducing soil loss under natural rainfall during reclamation, and
3. identify the probable causes of gully formations following installation of BGTs at NGGL.

The second experiment was targeted at the second broad goal. Using stockpiled topsoil (STP) as the main substrate, a trial was carried out to explore the effects of stockpiling on soil properties and organic amendments in promoting tree growth at the site. The hypothesis was that; (a) topsoil stockpiling as practiced at Newmont Ghana Gold Limited has adverse impacts on soil properties; and (b) amending stockpiled topsoil with organic materials, composted sewage sludge (CSS) and poultry manure (PLM), promotes the survival and growth of planted trees.

The third and last field experiment was directed at the third broad goal. This study explored the feasibility of using stockpiled subsoil (STS) as topsoil substitute for the reclamation activity



in situations where it is difficult to obtain topsoil or there is topsoil deficit. The hypothesis was that amendment of stockpiled-subsoil with poultry manure positively influences growth of trees and ground vegetation cover which promote better soil stabilization at degraded mine-sites.

The detailed findings of the three studies were each published in a peer-reviewed journal and are presented in this thesis as chapters two, three and four respectively. Chapter five entails the general summary and conclusions as well as implications for practice and recommendations further research.

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## CHAPTER TWO

### **Paper I: The potentials of biological geotextiles in erosion and sediment control during gold mine reclamation in Ghana**

Paul Kofi Nsiah and Wolfgang Schaaf

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#### **Abstract**

*Purpose* Soil erosion is a significant environmental impact of surface mining affecting the initial establishment of vegetation, especially on steep slopes, during reclamation. Consequently, we investigated the potentials of biological geotextiles constructed from two local plants, *Pennisetum purpureum* and *Broussonetia papyrifera*, in reducing erosion and sedimentation during reclamation at Newmont Ghana Gold Limited.

*Materials and methods* Six experimental plots were constructed on a 33% slope waste-rock, covered with a 70 cm layer of stockpiled subsoil. Concrete gutters, lined with silt fence, were installed at the lower end of each plot to collect eroded sediment. The two kinds of biological geotextiles, “York” mat and Elephant-grass mat, were used with bare ground as control in a randomized block design with two replicates each. Data on sediment yield was collected after each substantial rainfall. The performance of each geotextile in reducing soil loss was expressed as a percentage from the mean total sediment yield.

*Results and discussion* With total precipitation of 306 mm in the period April 18, to July 4, 2016, both Elephant-grass mat and “York” mat significantly ( $p < 0.05$ ) reduced soil loss by 56.6 % and 97.3 %, respectively, compared to the control, indicating both mats were effective in erosion and sediment control. The relatively high performance of York mat was mainly attributed to its more fibers that provided high surface cover (70 %) as well as flexibility of the fibers which enabled the mat to absorb more water during rainfall thus increasing its weight. This increase in weight promoted better drapability, with better erosion and sediment control.

Gully formations at the site were primarily due to high concentrated runoff flows from the top of reclaiming-benches, with time delays between completion of earthworks, geotextiles placement and seeding of plants as predisposing factors.

*Conclusions* The YM and the EM individually acted as cover and protected the highly erodible graded-mine slope against the erosive forces of tropical rain and runoff until vegetation establishment. Even so, planning and coordinating the reclamation program such that all earthworks are completed at the end of the dry season to enable geotextiles installation and plant seeding at the onset of rains, together with installation of temporary slope-drains in preventing gully formations from concentrated runoff flows, are considered to contribute significantly to the general reclamation success at NGGL and similar mine sites.

**Keywords:** Biological geotextiles, erosion and sediment control, mine reclamation, slope stabilization, surface mining, revegetation.

## **2.1 Introduction**

Mining is defined as the process of extracting minerals from the earth, which begins with the exploration for and the discovery of mineral deposits and continues through ore extraction and processing to the closure and remediation of worked-out sites (UNEP, 2000). The Ghanaian economy depends heavily on mining of minerals like gold, bauxite, diamond, manganese and recently oil, to derive the needed cash for her economic growth and development. The mining industry is the leading export earner accounting for about 42 % of Ghana's gross export revenue and 6.1 % GDP in 2012 (Ghana Chamber of Mines, 2014).

Despite significant contributions of mining to the development of Ghana and many other nations, mining operations can potentially result in sundry adverse impacts on the environment if proper management systems are not put in place (UNEP, 2000). Surface mining is considered as one of the most complete forms of human caused habitat alteration and degradation (Fischer and Fischer, 2006). Notable impacts include changes in the landscape; destruction of vegetation, topsoil, fauna and habitats; acid mine drainage; air and water pollution; noise and vibration (Conservation International, 2000; EIA Guide, 2010; Environment Australia, 2002; MINEO, 2000) and accelerated erosion (Wright, 2000). Soil erosion is a natural process; however, the process is accelerated by high soil disturbing anthropogenic activities such as surface mining (NRCS, 2006; Wright, 2000). Due to the negative impacts, most Ghanaians perceive discovery of minerals and mining as curse and are of the opinion that mining should not be tolerated by any government. The truth, however, is



that mining serves as foundation for the sustenance and development of man offering the opportunity to catalyse broad-based economic development, reduce poverty and assist countries in meeting internationally agreed development goals, including the Millennium Development Goals, when managed effectively and properly (UNGA, 2012).

### **2.1.1 The need for mine land reclamation**

Having realised the importance and benefits of mining to economic growth and development of man, the question arises as to how can mining be managed effectively and properly as promulgated by UNGA (2012)? Or better still, how can mining be conducted to achieve the full economic and social benefits and also ensure the environmental benefits are not relegated? A plausible answer to these questions is that mine proponents must have plans for reclamation prior to the onset of mine operation. Mine land reclamation is defined as either the restoration of mined land to its pre-mining conditions, or alteration to make it available for another productive use (Conservation International, 2000). Mine reclamation thus, guarantees a balance between mining the minerals for full economic and social benefits that mining promises and a proper way of ensuring the ecosystem is managed sustainably. With reclamation in view, mining should be seen as merely a land-use transformation, since the original ecosystem on a mined land can be restored to an equally or even a more productive level than it used to be prior to mining.

### **2.1.2 Challenges of mine land reclamation in Ghana**

Mine land reclamation in Ghana became mandatory after the enactment of the Ghana Environmental Assessment Regulation 1999 (GEAR, 1999). Regulation (23) requires mine proponents to have plans for reclamation and to post a Reclamation Security Bond. However, personal field observations and studies (Nsiah, 2008; 2012) have revealed most disturbed mine sites in Ghana have not been reclaimed. Even in cases where some mining companies made reclamation attempts, such attempts did not yield the desired results due to failure in adopting best reclamation management practices. Notably among these failures is the stabilization of slopes during the initial stages of re-vegetating the disturbed mine lands. Creation of slopes resulting from changes in land form is characteristic of surface mining due to the need to remove large volumes of materials such as waste-rock, topsoil, overburden and mine spoil and the demand to minimise total land to be disturbed by placing the materials removed. Thus, an increase in slope gradient relative to that present pre-disturbance is often favoured by land engineers because of the desire to minimise total disturbed land and the lesser economic cost afforded by steeper slopes (Rickson, 2003). Such increase in slope steepness can be directly

related to an increase in erosion rate since overland flow on steeper slopes has greater velocity, which increases the erosivity of the flow, both for detachment of soil particles and for the transport of already detached particles (Rickson, 2003; Wright, 2000).

An adequate vegetation cover can generally provide long-term soil protection against erosion. However, the establishment of vegetation is often counteracted during the early plant growth stages by the erosive forces of rain and runoff (Smets et al., 2007). During the initial stages of revegetation, rills and gullies are often created leading to the loss of topsoil and its living organisms as well as seeds and seedlings of diverse plant species (Smets et al., 2009). Biological geotextiles can serve as temporary replacement of the vegetative cover on steep erodible slopes, where vegetative growth is limited by erosive forces of rain and runoff (Smets et al., 2007; Ghosh et al., 2016). Biological geotextiles are therefore, possible temporary alternative for vegetation cover and can offer immediate soil protection on slopes (Hann and Morgan, 2006) to pave way for re-vegetating disturbed mine sites.

### **2.1.3 Biological geotextiles in erosion control and soil loss reduction**

Geotextile is defined as a fabric or synthetic material placed between the soil and a pipe, gabion, or retaining wall, to enhance water movement and retard soil movement, and as a blanket to add reinforcement and separation (ASAE, 1992). Geotextiles produced from man-made materials such as nylon, polypropylene, polyester, polyethylene etc. are referred to as synthetic geotextiles, whereas those made from natural materials (plants) are called biological or biodegradable geotextiles (BGTs), due to their general ability to undergo complete decomposition (Rickson, 2006). Despite synthetic geotextiles dominating the commercial market, BGTs are highly effective in erosion control and vegetation establishment, apart from the fact that commercially marketed synthetic ones are usually too expensive, especially in developing countries (Davies et al., 2006). According to the authors, BGTs are cost-effective if they are constructed using indigenous materials that are affordable and compatible with sustainable land management. The effectiveness of BGTs in decreasing soil loss mainly depends on several properties, such as per cent open area, mass per unit area, thickness, tensile strength, water-holding capacity, weight of mats per unit area when they are wet, design and drapability (Rickson, 2003; Sutherland and Ziegler, 2007). Soil and climatic conditions have also been shown to play major roles in the effectiveness of BGTs for soil erosion control (Rickson, 2003; Bhattacharyya et al., 2010b; Smets et al., 2007). Bio-geotextiles function in controlling erosion and runoff by targeting all the mechanisms of erosion in different ways. Their presence reduces the amount of splash erosion (Bhattacharyya et al., 2008; Bhattacharyya

et al., 2009; Bhattacharyya et al., 2010a; Rickson, 2003) by serving as a surface cover to intercept the kinetic energy of falling raindrops, thus targeting soil detachment. Furthermore, they reduce the direct effects of raindrops on surface soils and dissipate the kinetic energy of the raindrops, thus weakening surface sealing and crusting (Sutherland and Ziegler, 2007). The process increases infiltration rates of the covered surfaces relative to bare soil, thereby decreasing runoff levels. Again, they control runoff transport and soil deposition by their numerous cover providing surface roughness as well as creating several cross-drains that alter flow direction, impede overland flow velocities and modify the shear stress partitioning of overland flow (Rickson 2003; Thompson, 2001) keeping soil and seeds in place and thereby increasing chances of germination and vegetation growth (Pillai, 1994). The earth clothes absorb water during rainfall events, expand and increase their weight thereby adhering to the soil surface and enhance the drapability as they become saturated with water (Rickson, 2003; Sutherland and Ziegler, 1995).

#### **2.1.4 Field experimentations of BGTs**

There have recently been extensive studies on the use of BGTs constructed from several plant species in the erosion control industry. Among such researches include a pilot project on the potential contribution of palm-mat geotextiles to soil conservation (Davies et al., 2006), where the authors investigated the effectiveness of using BGTs constructed from *Borassus aethiopum* in decreasing water erosion. Their results suggest palm-mat geotextiles were effective for soil conservation, reducing soil losses by roughly two-thirds relative to bare control plots. A study by Bhattacharyya, et al. (2008) also investigated utilizing palm-leaf BGTs to conserve loamy-sand soil indicated sediment yield reduction effectiveness for Borassus and Burity mats were approximately 93% and 98% respectively compared with bare plot. Another study under the Borassus-Project by Smets et al. (2011) to evaluate the effectiveness of four kinds BGTs showed the BGTs reduced run-off depth and soil loss rates on average by 46 % and 79 % respectively, compared to the values for the bare soil. Under the same Borassus Project, Bhattacharyya et al. (2011b) investigated the effectiveness of the erosion control mats for soil and water conservation at eight different agro-environmental sites in six countries and their results indicated the BGTs were very effective for soil erosion control at all eight experimental sites, with the effectiveness in decreasing soil erosion rates by water ranging between 67 – 99 %. The result of a study by Jakab et al. (2012) has also shown both Borassus and jute geotextiles recorded over 80 % soil loss reduction compared to the value of uncovered plot.

Despite the numerous studies on the use of BGTs in erosion and sediment control in several parts of the world, such is not the case in Ghana. Currently, only few mining companies in Ghana, notably, Newmont Ghana Gold Limited (NGGL) utilizes BGTs constructed from the paper mulberry plant, *Broussonetia papyrifera*, locally called The “York” plant (YP), hence its name “York” mat (YM). The YM was developed by one Mohammed Bin Abubakaar for reclamation of the disturbed mine sites. However, prior to this study, there was no scientific data on the erosion-reducing effects of the YM as its performance had always been based on intuition or qualitative experience, rather than on quantitative scientific data. Furthermore, personal field observations about the application of the YM had revealed gullies being created at some reclaimed areas following deformation of the BGT before vegetation could be established (Fig. 2.1).



Figure 2. 1: Gully formations following application of the York Mat at NGGL.

Such slope failures could defeat the overall goal of reclaiming the disturbed mine-site to make it safe, stable and compatible with the surrounding landscape and end land-use, hence the need to address it.

### 2.1.5 Research questions, hypotheses and objectives

Having observed the gully formations following the application of the YM BGTs, the following questions were asked: How effective is the YM able to reduce soil loss? What might have caused gully formations in some reclaimed areas where the YM has been installed? Could the problem be attributed to the flexibility of YM that renders it not strong enough to resist the erosive forces of rain and run-off? If that is true, could the stems of *Pennisetum purpureum* (Elephant-grass), which is relatively rigid, be used to construct different kind of BGTs? Above

all, what will be the performance of the Elephant-grass mat (EM) and that of YM in erosion and sediment control?

The following hypotheses were postulated following the above questions: (1) Gully formation in some reclaimed areas at NGGL following application of YM BGTs is due to the flexibility of YM. (2) Biological geotextile constructed from relatively rigid plant parts, like the stems of the Elephant-grass plant (EP), will be more effective in erosion and sediment control compared to YM. The main goal of the study therefore, was to investigate the potentials of BGTs constructed from EP and YM in erosion and sediment control during reclamation at NGGL. The specific objectives were to (a) design and construct BGTs from the EP using an appropriate technology; (b) evaluate the performance of EP BGTs and that of YM BGTs in reducing soil loss under natural rainfall during reclamation, and (c) identify the probable causes of gully formations following installation of BGTs at NGGL.

## 2.2 The study area

The study was conducted at an active surface mine site of NGGL located between latitudes 6°40', 7°15', North and longitudes 2°15', and 2°45' West in Kenyase of the Brong-Ahafo Region, Ghana (Fig. 2.2).

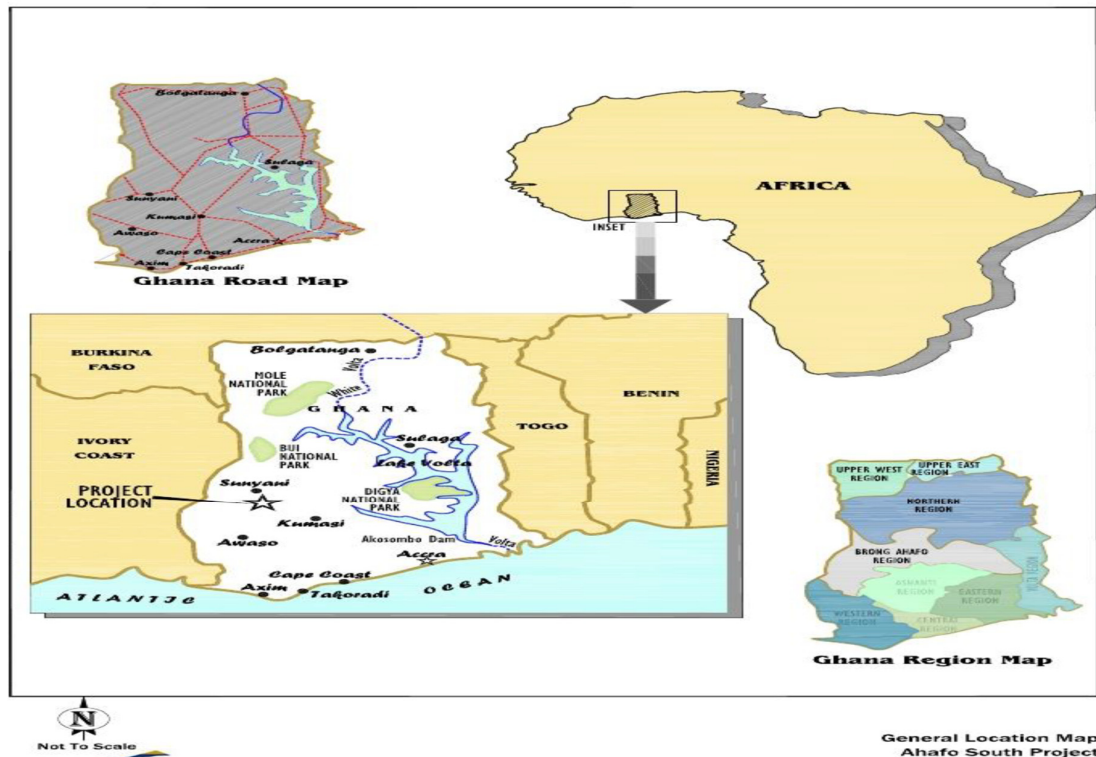


Figure 2. 2: The location of NGGL Project, Ahafo Kenyase (Source: NGGL 2015).

The climate is warm and humid with mean monthly temperature ranging from 23.9 °C to 28.4 °C. The soils are classified into the USDA Soil Taxonomy and the FAO World Reference Base for soil resource classification systems as mostly Ultisols (Acrisols and Nitisols) are on the uplands and mostly Fluvents (Fluvisols) and Inceptisols (Cambisols) in the lowlands (NGGL, 2015).

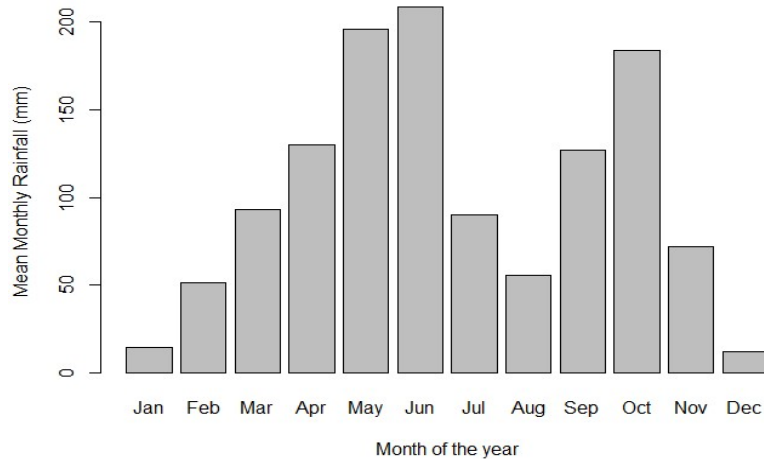


Figure 2. 3: A 12-year (2005 to 2016) monthly mean precipitation (mm) at NGGL, Ahafo-Kenyase (Source: NGGL weather station).

## 2.3 Methods

### 2.3.1 Design and construction of the Elephant-grass mat BGTs

Stems of the EP were taken from the field and cut into one-meter lengths. Each one-meter stick was split into four small sticks. Young leaves from *Raphia farinifera* were used as threads in weaving the EM BGTs by twisting the threads around the sticks as demonstrated in Fig. 2.4.



Figure 2. 4: Construction of Elephant grass mats in Kenyase.

### 2.3.2 Design and construction of experimental plots to evaluate the performance EM and YM

A waste-rock dump (WRD) at Amoma Pit was re-shaped and graded to form 33% slope and evenly covered with 70 cm layer of stockpiled-subsoil (STS). The experimental set-up was based on the method for the Quarry Life Award (QLA) project (Nsiah, 2012) which also mimicked that of the BORASSUS project (Smets et al., 2011). Six experimental plots, each measuring 14 m by 1 m, were designed (Fig. 2.5) and constructed (Fig. 6) from rectangular wooden boards. Half of the board's width (15 cm) was buried into the ground with the remaining half protruding above ground.

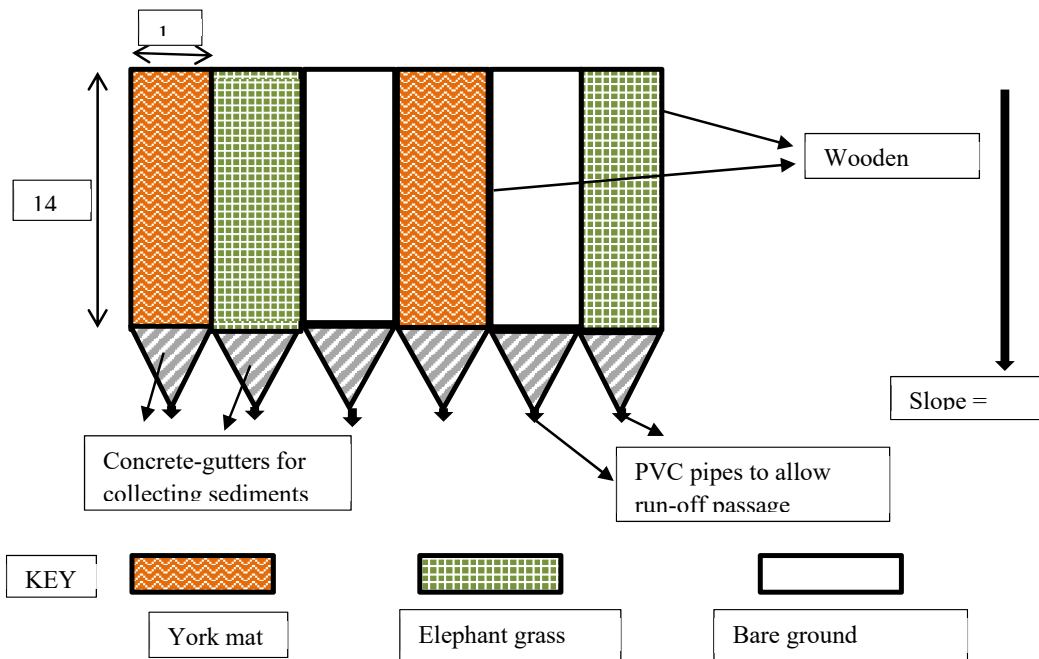


Figure 2. 5: The design of experimental field plot.

Concrete gutters, lined with silt fence, were constructed at the lower end of each plot for collection of sediment yield. To allow for run-off passage, PVC pipe was installed at the mouth of each gutter. A rain gauge was mounted to record the corresponding rainfall data. The two tested BGTs, YM and EM were used with bare ground as control, in a randomized block design with replication (Fig. 2.6).



Figure 2. 6: The constructed experimental field plot at the Amoma Pit.

### 2.3.3 Field data collection (measurement of sediment yield)

Data on sediment yield was collected from eroded sediment after each substantial storm (Fig. 2.7) and the corresponding rainfall figures recorded (mm). The performance of the BGTs in reducing sediment yield was expressed as a percentage from the mean total Sediment Yield (SY) following (Sutherland, 1998) method; where:

$$\text{Percentage Sediment Yield (SY) effectiveness} = \left( \frac{\text{Bare soil SY} - \text{BGTs covered SY}}{\text{Bare soil SY}} \right) * 100$$

### 2.3.4 Site characterization

The STS was characterized prior to the placement of BGTs. Six soil cores were randomly collected from the experimental site with the help of a spade. All six samples were placed in a clean plastic bucket to make one composite sample. After some mixing in the bucket, the content was placed onto a clean plastic tray for further mixing and division until a representative sample of about one kg was placed in a brown paper bag. Duplicate and triplicate samples were taken following the same method and all samples were sent to the laboratory for analyses. Particle size analysis was conducted by the hydrometer method (Bouyoucos, 1927)



whilst textural class was determined according to the United States Department of Agriculture soil texture classification system. Organic matter content was determined by loss of weight on ignition with the aid of Muffle furnace model L9/S (Motsara and Roy, 2008). Bulk density was determined by the intact core method and weight determination after oven-drying (Brady and Weil, 2008). Soil pH was determined with an electrode in 5:1 water to soil extract Motsara and Roy (2008).



Figure 2. 7: First sediment yield collection and weighing after installation; left (control) = 36.8 kg; middle (YM) = 0.8 kg; right (EM) = 3.5 kg.

### 2.3.5 Statistical analysis

Data analyses and visualization were done with R statistical software version 3.2.4 and SPSS Version 25. Descriptive statistics (mean and standard deviation) of all repeated measurements in comparing the effectiveness of the treatments in reducing soil loss during each of the 12 storm events, was done with SPSS. Pearson's correlation (R) between amount of rainfall and total sediment yield for each treatment was obtained with the Hmisc package, whilst scatter plots were drawn with ggplot2.

## 2.4 Results

### 2.4.1 The constructed Elephant-grass mat

The study made it possible to construct BGTs from the EP called Elephant-grass mat (EM) by weaving threads of *Raphia farinifera* leaves around the sticks of EP. The introduction of the threads was seen as major improvement compared to an earlier one manufactured during the QLA project (Nsiah, 2012) as the threads made it possible to weave the mats into longer lengths. Again, the threads allowed easier folding of the mats thus making their packaging and transportation easier and more convenient.

### 2.4.2 Subsoil characterization before placement of BGTs

Characterization of the subsoil used for the experiment (Table 2.1) showed the soil was sandy-loam according to the United States Department of Agriculture (USDA) soil texture classification system.

Table 2. 1: Characterization of stockpiled subsoil at NGGL.

Parameter	Value
Sand (%)	66.59 ( $\pm$ 0.88)
Silt (%)	22.32 ( $\pm$ 1.10)
Clay (%)	11.09 ( $\pm$ 0.40)
Bulk density (g cm <sup>-3</sup> )	1.30 ( $\pm$ 0.01)
Organic matter (%)	3.83 ( $\pm$ 0.02)
Organic carbon (%)	2.22 ( $\pm$ 0.01)
pH	6.60 ( $\pm$ 0.10)

### 2.4.3 Evaluation of the performance of YM and EM in reducing soil loss

In all, 12 substantial rainfall events were recorded within the experimental period (April 18 to July 4 2016) with total precipitation of 306 mm (Table 2.2).

A substantial rainfall here implies any rainfall that was able to cause soils to be eroded from the experimental plots. The first rainfall of 18.2 mm was recorded on April 22, whilst the last rainfall (12.7 mm) for the major raining season of 2016 was recorded on July 4. The least rainfall (9.6 mm) occurred on May 11 with the highest (70.1 mm) occurring on May 19 (Fig. 2.8).

Comparison of relative performance showed both EM and YM significantly ( $p < 0.05$ ) reduced soil loss by 56.6 % and 97.3 %, respectively, compared to the control (Fig. 2.9).

A Pearson's correlation, at 95 % confidence interval showed strong positive correlations between rainfall (mm) received and corresponding mean sediment yield (kg) for all treatment plots EM and YM and control, with the respective  $R^2$  values of 0.85, 0.84 and 0.88 (Fig. 2.10). All p-values were  $< 0.05$ .

Table 2. 2: Mean sediment yield (Kg) and standard deviation of the 12 storm events during the experimental period with corresponding rainfall figures (mm).

Date	Rainfall (mm)	York mat	Elephant-grass mat	Control
22/04/2016	18.2	0.50 (0.42)	7.85 (5.58)	49.00 (17.20)
03/05/2016	23.5	2.60 (1.27)	18.45 (5.16)	43.10 (18.34)
11/05/2016	9.6	1.80 (1.83)	5.90 (5.09)	15.50 (0.96)
13/05/2016	19.8	1.75 (1.48)	19.20 (8.06)	30.85 (7.99)
19/05/2016	70.1	4.15 (2.75)	70.30 (2.9)	104.60 (18.52)
26/05/2016	61.9	3.20 (2.82)	55.75 (17.74)	100.75 (3.18)
10/06/2016	24.9	0.90 (0.84)	26.20 (9.47)	79.30 (1.27)
13/06/2016	22.1	0.75 (0.21)	26.50 (2.68)	63.45 (9.68)
16/06/2016	19.1	0.69 (0.49)	23.75 (2.05 )	54.65 (9.54 )
24/06/2016	14.5	0.45 (0.35)	13.25 (1.34)	47.50 (8.20 )
28/06/2016	10.2	0.30 (0.28)	10.40 (1.27)	38.15 (7.99 )
04/07/2016	12.7	0.20 (0.14)	6.2 (1.55)	29.40 (4.10 )

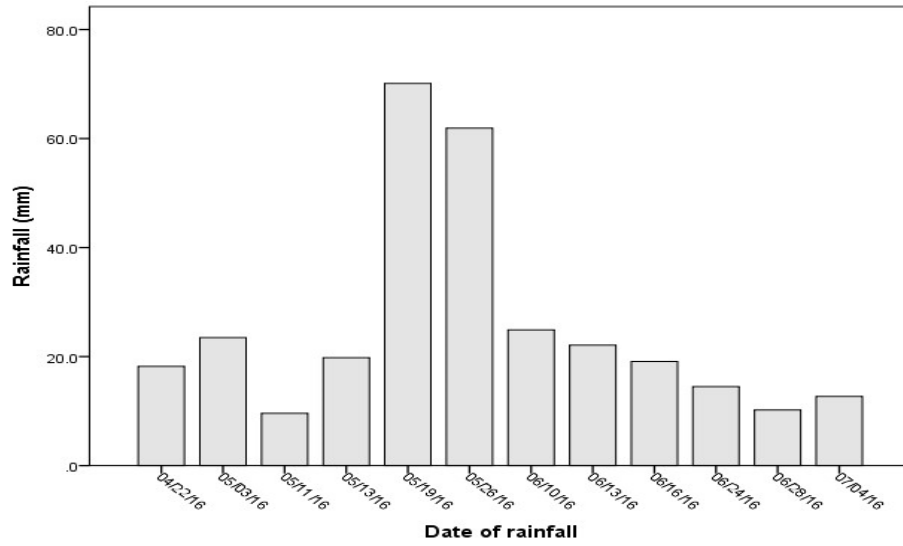


Figure 2. 8: Rainfall distribution during the experimental period (18/04/2016 – 04/07/2016).

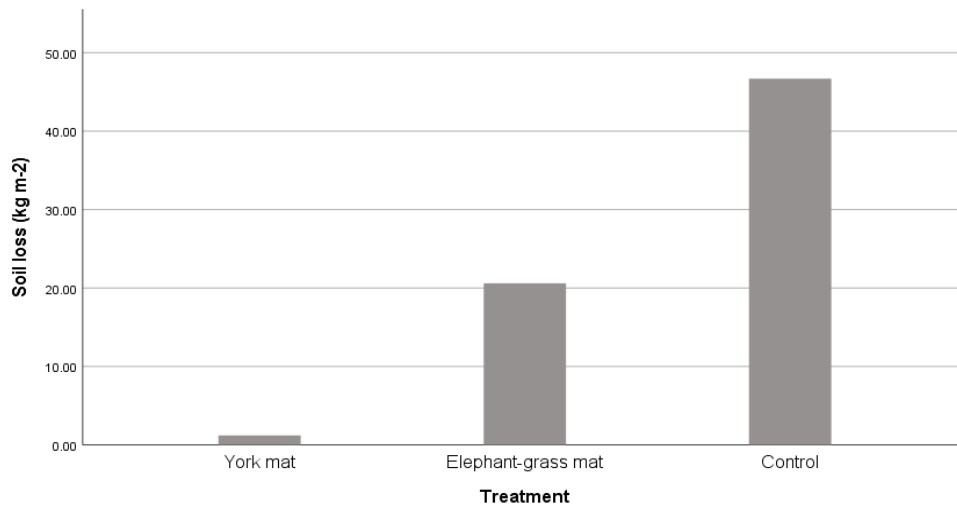


Figure 2. 9: The performance of BGTs in reducing soil loss at NGGL.

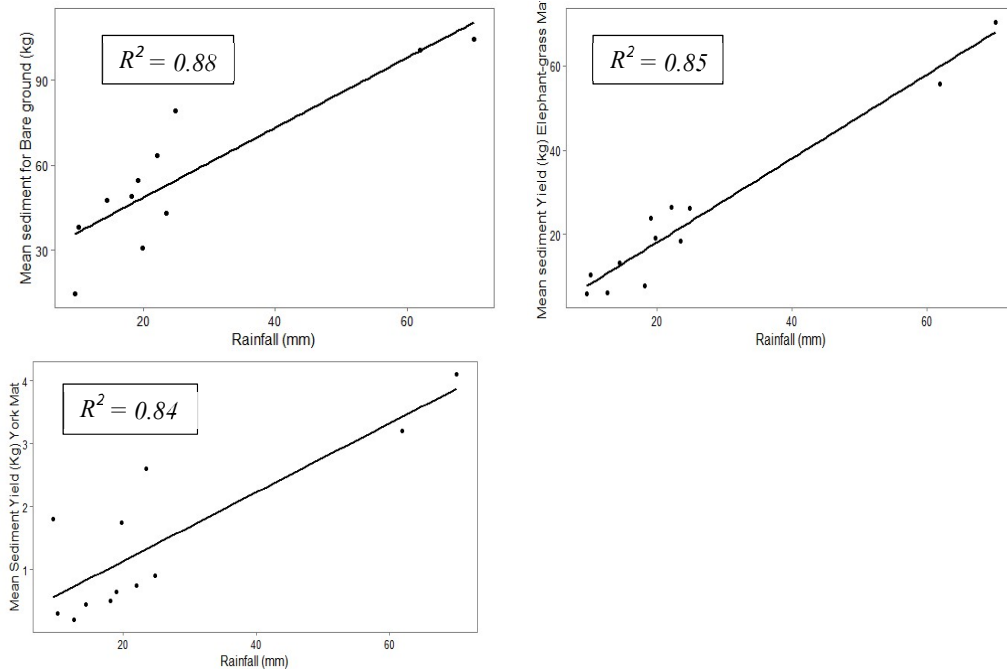


Figure 2. 10: A Pearson's correlation showing effect of rainfall quantity on soil loss for (a) control, (b) Elephant grass mat and (c) York mat treatments.

#### 2.4.4 Causes of rill and gully formations in reclaimed areas at NGGL

A major reason for the introduction of the Elephant grass mat into the study was to find out if rill and gully formation in those reclaimed slopes at NGGL, where the YM had been installed, was as a result of the softness or flexibility of the YM. However, critical visual field observations during the study revealed the main cause of such rill and gully formation was due primarily to the high concentrated runoff flows from the top of the reclaiming-benches (Fig. 10a and 10b) and not as a result of the softness or flexibility of the YM as initially thought. A secondary source of the problem was attributed to the unnecessary time delays between completion of final earthworks (topsoil re-application and grading) and beginning of soil stabilization and revegetation activities (Fig. 2.11).



Figure 2. 11: Gully formations during reclamation at NGGL.

## 2.5 Discussion

### 2.5.1 Performance of YM and EM BGTs in reducing soil loss

The study intentionally selected a site where only SSS had been re-applied as a substrate for revegetation. Characterization of the SSS revealed high sand and low silt and clay with moderate organic matter content. These soil properties coupled with the vulnerability of the newly reclaimed site to factors controlling erosion and sedimentation (Brady and Weil, 2008) such as steep topography (graded slope of 33 %), high intensity tropical rainfall, lack of surface cover and poor soil structure rendered the site to be highly erodible, based on the Universal Soil Loss Equation (Wischmeier and Smith, 1978). Such site was useful in the study to enable effective evaluation about the performance of the two BGTs in soil conservation against the bare plot (control).

Although most researchers investigating performance of BGTs in soil loss reduction considered longer duration for the experiment (Bhattacharyya et al., 2008; Davies and Booth, 2006; Jakab et al., 2012; Smets et al., 2011) this study restricted data collection on sediment yield for only the initial three-month period: from April 18 (beginning of experiment) to July 4 (end of the first rainy season in 2016). This was because the site is a typical humid tropical climate that possesses a bi-modal rainfall pattern (Fig. 3) with distinct wet and dry seasons. Generally, the major rainfall begins in mid-March and ends in mid-July, with the minor rains commencing on early September and ending in mid-November. This generates two dry seasons, major drought usually from mid-November to mid-March and a minor drought from mid-July to end of August. At the beginning of the minor season in September, vegetation had already been established on the plots thereby preventing further erosion and sedimentation. The

observation was similar to the findings of the QLA project (Nsiah, 2012) where application of BGTs for vegetation establishment in the major raining season demonstrated vegetation taking over the role of the geotextiles at the beginning of the minor season in September. Hence, the initial three-month period was the time necessary for the geotextiles to control erosion and sedimentation for effective vegetation establishment.

The study further restricted data collection to only soil loss reduction (sediment yield) and not runoff volumes because of some observation made during the previous field experiment of the QLA project (Nsiah 2012), where all 20-liter containers placed in the mouth at the PVC pipes for collection of runoff always overflowed after each storm. Larger containers of probably over 100-liter capacity were thus needed in order to collect the huge volumes of runoff from such tropical storms. The placement of such large volume containers at the mouth of the PVC pipes for runoff collection was practically not feasible during the study. Therefore, only the effect of the mats in reducing soil loss, which was a major challenge at the site, was considered in this study.

The relatively high performance of YM in reducing soil loss was mainly attributed to the numerous fibers of the YM that provided more surface cover (70 %) which protected the soil against disintegration due to rain splash, as were also observed in other studies (Bhattacharyya et al., 2008; and Kalibova et al., 2016; Rickson, 2003). In addition, the fibers of YM were flexible, with high water-holding capacity, enabling the mat to absorb more water during rainfall, thereby increasing its weight to more than four times the dry weight. This increase in weight promoted better adherence to the soil surface or drapability (Bhattacharyya et al., 2011a; Rickson, 2006), which limited soil detachment due to runoff. Moreover, the myriad fibers of YM, many of which were laid across the direction of runoff flow, acted as barriers in reducing the raindrop velocity (Thompson, 2001) of tropical storms on the steep slopes. The fibers which were firmly attached to the soil surface in all directions helped in the retention of the few disintegrated sediments that were being transported by the runoff, thereby effectively controlling erosion and sedimentation. The EM, on the other hand, had relatively low surface cover (45 %), thus limiting its performance in erosion control compared to YM. The semi-rigid nature of the fibers of EM, which we initially thought could result in better erosion and sediment control, could only cause a 1.5 times increase in weight after saturation with rain water, thus, resulting in poor contact between the EM and the soil surface. This lack of contact between EM and the soil resulted in more sediment detachment and further transportation by runoff underneath, thereby reducing EM potential ability in erosion control and sediment retention, compared to YM. The findings in this study are in accordance with

that of previous studies (Chen et al., 2011; Kalibova et al., 2016; Kumar, 2013) who found the performance of BGTs in reducing soil loss to decrease as the geotextiles material's rigidity increases. Notwithstanding the difference in their performance, in the absence of any vegetation both the YM and the EM acted as cover factor (C) according to the Universal Soil Loss Equation (Wischmeier and Smith, 1978) and protected the highly erodible mine slope and allowed vegetation to sprout and establish through their openings. Both mats were therefore, considered as effective biotechnical slope stabilization and soil conservation tools for protecting graded mine slopes against the highly erosive forces of tropical rain and runoff until vegetation establishment at NGGL. The study foresees the world-wide applicability of the two tested BGTs in the erosion and sediment control industry as the low-cost mats could be produced in commercial quantities and conveniently packaged in containers to be shipped from Ghana to any part of the globe.

### **2.5.2 Gully formations following application of BGTs in some reclaimed sites at NGGL**

Gully formations usually seen in some reclaimed sites at NGGL were visually observed to have primarily resulted from the high concentrated runoff flows that originate from the top of the reclaiming-benches, and not as a result of the flexibility of YM, as the study hypothesised. Runoff water of the high tropical storm, which begins from the top of the benches (crest), is ideally supposed to be infiltrated into the soil and the excess evenly transported over the slope surface to the bottom (toe). However, in some few areas, runoff flows were not evenly distributed causing such high concentrated flows that the installed BGTs could not resist, resulting initially in formation of rills and subsequently, to gully formation or slope failure. A secondary source was attributed to the delays in time between completion of final earthworks (topsoil re-application and loosening), placement of BGTs and seeding of plants, especially, where earthworks were being carried out in the raining season. At these periods, factors controlling erosion and sedimentation (Wischmeier and Smith, 1978) such as steep topography, high intensity tropical rainfall, lack of surface cover and poor soil structure (Brady and Weil, 2008; Wright, 2002) are at their fullest potential, rendering the site (beginning from ground zero) extremely vulnerable to erosion. Any delays in undertaking soil stabilization and revegetation activities as soon as completion of final earthworks could imply one is planning for such rill and gully formations or slope failures which can thwart the entire reclamation success.

As a panacea in overcoming the problem of rill and gully formations and to guarantee complete reclamation success at NGGL, a combination of BGTs installation with other best



management practices such as the installation of temporary slope-drains with berms and diversion channels at the crest of benches to help divert up-gradient surface runoff and safely convey it into drainages down slope, as suggested by Wright (2002), and which is beyond the scope of this research, should be adopted. Moreover, planning and coordinating the reclamation programme such that all earthworks can be completed at the end of the dry season in mid-March, to give way for BGTs placement and simultaneous seeding of crops and trees as soon as the major rains begin is seen to contribute significantly to reclamation success at NGGL and similar mine sites in Ghana and beyond.

## **2.6 Conclusions**

The study was conducted to investigate the potentials of EM and YM in erosion and sediment control during mine reclamation at NGGL. The YM was better in reducing soil loss (97.3 %), which was mainly attributed to its numerous fibers that ensured more surface cover (70 %) in limiting soil detachment due to rain splash. In addition, the fibers were flexible with high water-holding capacity, which promoted better drapability, enabling the YM to serve as cross-drain barriers that reduced velocity of the high tropical runoff and further aided in sediment retention. The EM, on the other hand, had relatively low surface cover (45 %), the fibers of which had poor water-holding capacity that resulted in relatively poor drapability, thus limiting its ability in arresting soil detachment, transport and deposition (56.6 %). The effectiveness of the tested biological geotextiles in reducing soil loss was directly correlated with the percentage cover and flexibility of the respective mat, thus rejecting the study hypothesis. Notwithstanding the difference in their performance, the YM and the EM individually acted as a cover factor and protected the highly erodible graded-mine slope against the erosive forces of tropical rain and runoff until vegetation establishment at NGGL.

The problem of rill and gully formations in some areas at NGGL following installation of YM BGTs was primarily attributed to the high concentrated runoff flows from the top of reclaiming-benches, with time delays between completion of earthworks, placement of BGTs and seeding of cover crops as predisposing factors. As a proposed solution in overcoming the gully formations and to ensure reclamation success at NGGL, the study recommends a further research into the installation of temporary slope-drains in combination with water-retaining berms and diversion channels, besides BGTs installation. Even so, planning and coordinating the reclamation programme such that all earthworks can be completed at the end of the dry season in mid-March to give way for BGTs placement and plant seeding at the onset of the

major rains is seen to contribute significantly to the general reclamation success at NGGL and similar mine sites in Ghana and beyond.

## **2.7 Acknowledgements**

Thanks to the German Academic Exchange Service and the Government of Ghana Scholarship Secretariat for co-funding this study. We are grateful to Newmont Ghana Gold Limited for granting access in conducting the field experimentation at their mine site.

## **2.8 Conflict of Interest**

The authors declare that they have no conflict of interest.

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## CHAPTER THREE

### **Paper II: Effect of Topsoil Stockpiling on Soil Properties and Organic Amendments on Tree Growth during Gold Mine Reclamation in Ghana**

Paul Kofi Nsiah and Wolfgang Schaaf

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#### **Abstract**

Topsoil is a valuable resource and regarded as the most critical and key component in any successful revegetation following mining activities. Consequently, salvaging and stockpiling topsoil for use in future reclamation is encouraged in mine operations. Studies have, however, demonstrated topsoil stockpiling has adverse impacts on soil properties and that stockpiled topsoil would require organic amendment to promote plant growth. This study was therefore undertaken with the hypothesis that (a) topsoil stockpiling as practiced at Newmont Ghana Gold Limited has adverse impacts on soil properties and (b) amending stockpiled topsoil with organic materials, composted sewage sludge and poultry layer manure, promotes the survival and growth of planted trees. A waste rock dump measuring 36m by 45m was graded and covered with a 70 cm layer of stockpiled subsoil followed by a 30 cm layer of stockpiled topsoil. Soil samples, with three replications, were collected at random from the experimental site and from a nearby un-mined, agricultural site used as reference, for determination of pH, nutrients, organic matter, electrical conductivity, effective cation exchange capacity, base saturation, bulk density and texture. Poultry layer manure (PLM), composted sewage sludge (CSS), and no amendment (control) were the treatments. Potted-seedlings of five forest tree species; *Terminalia superba*, *Terminalia ivorensis*, *Mansonia altissima*, *Kola gigantea* and *Cedrela odorata*; were planted in May 2016, followed by application of 1 kg and 0.5 kg (dry weight) of the PLM and the CSS respectively, per tree. Diameter and height data of all planted trees and number of surviving trees were collected twice to determine tree growth and survival. Statistical analysis revealed that topsoil stockpiling did not have any significant adverse impact on the measured soil properties, compared with the reference plot. One-way ANOVA combined with LSD and Duncan post-hoc tests ( $\alpha = 0.05$ ) also indicated no significant influence of organic amendments on tree growth. Competition from herbaceous plants due to ineffective weed control was observed to be the main driving factor hindering survival and growth of planted trees. Further study to compare planting the intended tree species

concurrently with ground cover species in the first growing season combined with adequate weed control to influence tree growth and survival at the site, to the application of organic amendments is warranted.

Key words: Topsoil, mine-reclamation, organic amendment, revegetation, soil properties, trees species

### **3.1 Introduction**

Mining operations involve the use of heavy equipment to clear vegetation as well as remove soil and rock fragments, resulting in the disturbance of landscape aesthetics and soil components such as soil horizons and structure, organic matter (OM), soil microbial population and nutrient cycles that are crucial to supporting plant growth and ecosystem sustenance (CI, 2000; DOEC, 2005). Without proper management and regulations in place, these activities, along with construction of access roads and other ancillary facilities, can potentially result in severe disturbance or complete destruction of the soil and water resources, landscapes, vegetation and habitats (DOEC, 2005; Reuter, 1997; Wright, 2002). Leaving natural processes alone to repair such damages may take many years; hence the urgent need to help nature heal itself from such wounds in a relatively short time period through mine land reclamation

Mine land reclamation has been defined as either the restoration of mined land to its pre-mining conditions, or alteration to make it available for another productive use (CI, 2000). Ghana Environmental Assessment Regulations, (L.I. 1652), established in 1999, mandates large-scale mine proponents to reclaim their mine lands. However, personal field observations and studies have revealed most disturbed mine sites in Ghana have not been reclaimed (Nsiah, 2008; Nsiah, 2012). Even in cases where mining companies made reclamation attempts, such efforts could not produce any favourable outcome due to the failure in adopting best reclamation management practices. Notable failures have included poor stabilization of slopes against erosion and sedimentation (Nsiah and Schaaf, 2018) and a lack of either topsoil application or amendment with alternative material as a substrate for revegetation during the reclamation process.

Topsoil generally refers to the A horizon of the soil which is usually darker and more fertile than the layer below (subsoil) because of the accumulation of organic matter (Rollett et al., 2015; Wright, 2002). Topsoil is a valuable resource and regarded as the most critical component in any successful reclamation since it contains the building blocks for plant growth;

seeds and other plant propagules, soil biota such as fungi and bacteria, OM and much of the more labile plant nutrients that aid in promoting the emergence and growth of pioneer and other planted species on newly reclaimed lands (CI, 2000; DOEC, 2005; Reuter, 1997; Wright, 2002). Hence, salvaging and stockpiling topsoil during mining and reserving it for future use is critical to ensuring successful reclamation (CI, 2000; Reuter, 1997; Wright, 2002). Consequently, Newmont Ghana Gold Limited (NGGL) a mining company operating surface mines at Kenyase in the Bong-Ahafo Region of Ghana, salvages all topsoil and stockpiles it for future reclamation. Additionally, all subsoil is stripped and stockpiled separately.

Long-term topsoil stockpiling has been shown to decrease soil organic matter (SOM) content due to oxidation reactions by soil microbes (Wells and Potter, 1986). Other studies have demonstrated topsoil stripping and stockpiling to have major adverse effects on the physical, chemical and biological properties of the soil resource such as loss of OM (Abdul-Kareem and McRae, 1984; Akala and Lal, 2000; DOEC, 2005; Visser et al., 1984) reduction in the populations of essential microbes such as bacteria, fungi, actinomycetes and algae (Miller and Cameron, 1976) as well as mycorrhizal infection potential (Stark and Redente, 1987). Other effects include compaction and consolidation during storage which deteriorate soil structure (Harris et al., 1989). These reports suggest topsoil stockpiling can eventually lead to reduced nutrient cycling and lower availability of nutrients (DOEC, 2005; Stark and Redente, 1987), which can potentially impair the entire revegetation and reclamation success (Reuter, 1997).

Organic amendment (OA) has been demonstrated to contain high quantities of major plant nutrients and can also be a valuable source of OM, which can improve soil physical, chemical and biological properties (Larney and Angers, 2012; Wall, 2014) following disturbances such as mining. Organic amendment is a collective term used to describe materials rich in OM that are either a by-product of an existing process, such as biosolids (i.e. treated sewage sludge), or materials that have been produced as a result of some form of recycling process, such as compost (SNIFFER, 2010). Bending et al. (1999) maintain that SOM content, nutrient supply and pH are usually the most important determinants of the suitability of a disturbed site for restoration. Subsequently, Wright (2002) and DOEC (2005) emphasised applying OA with stockpiled topsoil (STP) as a vital management practice to improve the supply of nutrients and soil physical and chemical characteristics. Using OA for reclamation has also been described as being mutually beneficial wherein waste products from agriculture, forestry and urban areas help to meet land reclamation goals (Larney and Angers, 2012; Reuter,



1997). Consequently, NGGL applies composted sewage sludge (CSS) as OA with the STP to enhance revegetation success during reclamation.

In this study, the effect of topsoil stockpiling on soil properties and OA on tree growth were investigated. The hypothesis was that (a) topsoil stockpiling at NGGL will cause significant adverse impacts on soil properties and (b) amendment of STP with organic materials like composted sewage sludge and poultry layer manure will significantly promote survival and growth of planted trees at the site.

## **3.2 Methods**

### **3.2.1 Site location and description**

The study was conducted at an active surface mine site of NGGL located between latitudes 6°40', 7°15', North and longitudes 2°15', and 2°45' West, in Kenyase of the Brong-Ahafo Region, Ghana (Fig. 3.1).

The NGGL Ahafo-South project comprises facilities and services for mining and processing of approximately 105 million tonnes of ore being extracted from four open pits. The area falls within the wet semi-equatorial climatic zone of Ghana and is characterized by an annual double maxima rainfall pattern occurring from mid-March to early July and from early September to mid-November, with mean annual rainfall of 1,232 mm (Nsiah and Schaaf, 2018). The climate is warm and humid with mean monthly temperatures ranging from 23.9°C to 28.4°C. The soils are classified according to the USDA Soil Taxonomy and the FAO World Reference Base as Ultisols (Acrisols and Nitisols) on the uplands and Fluvents (Fluvisols) and Inceptisols (Cambisols) in the lowlands (NGGL, 2015). The area lies within the Moist Semi-Deciduous Zone Northwest Sub-type with emergent tall trees often exceeding 50 m in height (Hall and Swaine, 1981).

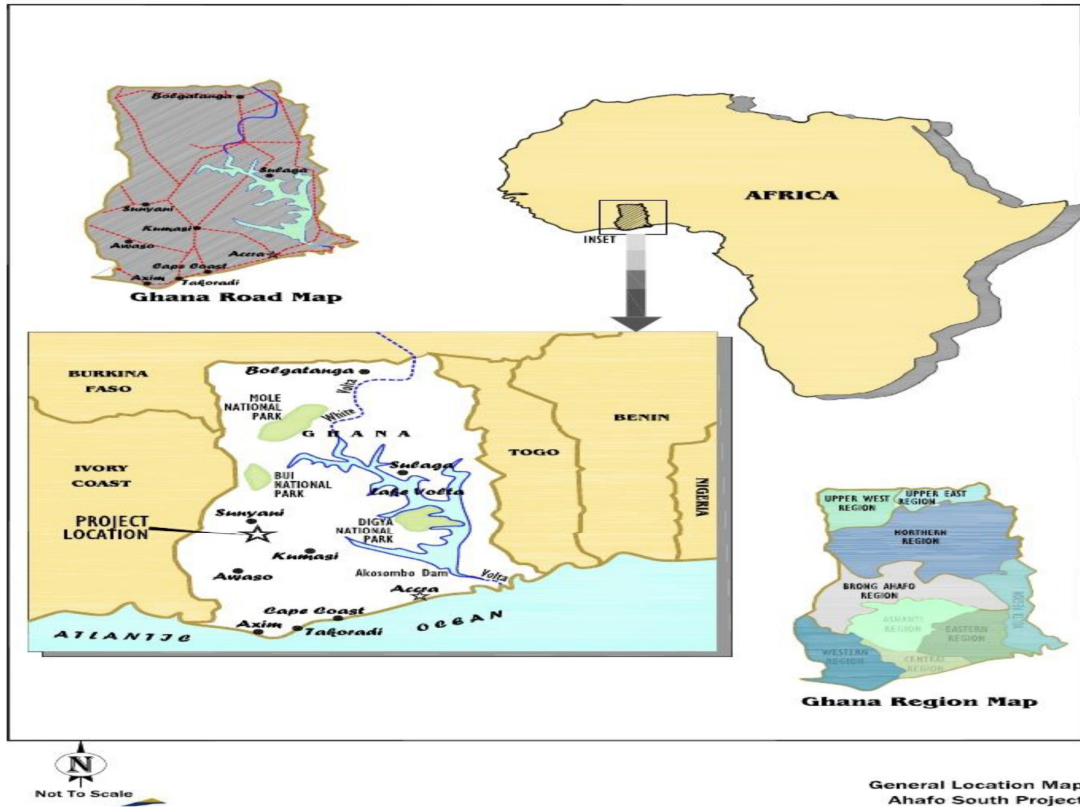


Figure 3. 1: The site location of NGGL, Ahafo-South, Kenya (Source: NGGL, 2015).

### 3.2.2 Land reclamation methods

The field trial was conducted on a waste rock dump, generated from the excavation and extraction of rocks that surrounded gold-bearing ore at the Amoma Pit, but which did not contain the metal in commercial quantities. Both the topsoil and subsoil were separately salvaged and stockpiled by the company prior to mining in 2009 for replacement during the reclamation phase. In order to maintain soil quality upon stockpiling, the salvaged topsoil was covered with biological geotextiles (BGTs) to control erosion and seeded with deep-rooted perennial plants in 2009. A site measuring 36m (vertical) by 45m (horizontal) was demarcated for this experiment under a concurrent reclamation approach. The waste rock dump was evenly graded to form a three-(vertical) to one-horizontal (3:1) slope and evenly covered with a 70 cm layer of stockpiled subsoil (STS), followed by a 30 cm layer of the STP (Fig. 3.2), generating a substrate depth of 1 m for revegetation.



Figure 3. 2: Replacement of stockpiled subsoil (left) and stockpiled topsoil (right).

The site was then scarified (ripped) across the slope to a depth of about 20 cm (Fig. 3.3) to minimize compaction and promote surface roughening and water infiltration. Further soil stabilization treatments included installation of “York” mat BGTs for erosion and sediment control (Nsiah and Schaaf, 2018), seeding bermuda grass (*Cynodon dactylon*) as cover crop and vegetative plantings of Vetiver grass (*Chrysopogon zizanioides*) in parallel terraces across the slope (Fig. 3.3).



Figure 3. 3: Scarification after STP re-instatement (left), BGTs installation and vegetative planting of Vetiver grass stalks (right).

### 3.2.3 Soil sampling and analyses

In order to evaluate any influence of topsoil stockpiling on soil properties, soil samples were randomly taken from six soil cores to a depth of 30 cm (depth of the replaced topsoil) with soil auger in May, 2016. All six samples were placed in a clean plastic bucket to make

one composite sample. After some mixing in the bucket, the content was placed onto a clean plastic tray for further mixing and division until a representative sample of about 1 kg was placed in a brown paper bag (Motsara and Roy, 2008). According to Larney and Angers (2012), a prevalent feature of degraded or disturbed soils is low organic matter content compared with adjacent undisturbed areas. Therefore, six soil cores were taken to a depth of 30 cm from a nearby un-mined site and bulked to make a single composite sample that was used as a reference (REF) in judging the quality of the STP. The reference site was a Cocoa (*Theobroma cacao*) farm, as the land surrounding the mine site had been affected by various farming activities. Separate samples were taken with a 100 cm<sup>3</sup> metal ring core to a depth of four centimeters for bulk density determination. All soil samples were taken with three replications and sent to the laboratory for determination of pH, nutrients, SOM, electrical conductivity (EC), effective cation exchange capacity (ECEC), base saturation (BS), bulk density and texture.

Prior to analyses, all soil samples, except those used for bulk density determination, were air-dried and sieved through a 2-mm mesh. Soil pH and conductivity were determined using multi-parameter PC 300 series electrode in 5:1 soil to water suspension (Motsara and Roy, 2008). Total phosphorus (P) was determined by the blue complex molybdate and thiophosphate in acid solution and analyzed using Buck Scientific Spectrophotometer (BSS) model 280 G (Motsara and Roy, 2008). For exchangeable bases, sodium (Na) and potassium (K), were determined by volumetric Sodium tetraphenyl boron method after dry ashing digestion of the soil sample and analyzing with a Jenway flame photometer model PFP7, whilst that of calcium (Ca) and magnesium (Mg) were analyzed using a Spectrophotometer (BSS 280 G), after extraction by ammonium acetate (Motsara and Roy, 2008). Exchangeable acidity due to hydrogen (H) and aluminum (Al) was extracted using 0.1N KCl solution and the filtrate titrated with 0.05N NaOH to colorless end point. Exchangeable acidity (Al and H) was determined by adding 4mls of 3N to the extract and titrated with 0.05N HCl to a pink end point.

The ECEC was calculated as the sum of exchangeable bases and acidity, and BS was calculated as the percentage of the base cations (Na, K, Mg and Ca) of ECEC (Hazleton and Murphy, 2007). Loss of weight on ignition method was employed for the determination of SOM and organic amendment samples with the aid of a muffle furnace model L9/S (Motsara and Roy, 2008). Particle size analysis was conducted by the hydrometer method (Bouyoucos, 1931) and textural class was determined according to the United States Department of Agriculture soil texture classification system. Bulk density was determined using undisturbed

soil cores collected in a 100 cm<sup>3</sup> metal ring core and weight was determined after oven-drying (Brady and Weil, 2008).

### 3.2.4 Tree planting and organic amendment application

The demarcated site was divided into three experimental plots each measuring 36 by 15 m and the following OA treatments were randomly assigned:

- no amendment, (control).
- amendment with poultry layer manure (PLM).
- amendment with composted sewage sludge (CSS).

In May 2016, six-month old potted-seedlings (nursery transplants) of the indigenous tree species *Terminalia superba*, *Terminalia ivorensis*, *Mansonia altissima* and *Kola gigantea* together with *Cedrela odorata* (exotic species) were selected for planting. For each treatment, 15 seedlings each of *T. superba* and *C. odorata* and nine seedlings each of *T. ivorensis*, *M. altissima* and *K. gigantea* were randomly planted at a spacing of 3 m × 3 m, with the help of bamboo pegs which were not in regular lines, resulting in an approximate density of 1,100 trees per hectare. Four of the species, *T. superba*, *T. ivorensis*, *M. altissima* and *K. gigantea*, were selected because they are native to the region whereas *C. odorata*, though an exotic species, was selected for its high adaptability and fast growth rate. Additional selection criteria were based on their high commercial values (high demand for their wood products both locally and abroad) and availability of their seedlings in the local nurseries. Some of the seedlings were obtained from the NGGL nursery stock whereas others were purchased from a nursery stock belonging to the University of Energy and Natural Resources, Sunyani, in the Brong-Ahafo Region of Ghana.

Two weeks after tree planting, the PLM and the CSS were applied to each of the individual trees in their respective plots by first digging a 10 cm deep trench with a 50 cm diameter around each planted tree, followed by placement of the respective amendment material and finally covering with soil. The PLM was applied at a rate of 1 kg (dry weight) per tree giving a total of 1.1 tonne per hectare, whereas the CSS was applied at a rate of 0.5 kg (dry weight) per hectare making a total of 0.55 tonne per hectare. The PLM, obtained from a layer-poultry farm, was in abundance, but the CSS, received from NGGL's Sewage Treatment Plant after composting, was of a limited quantity which necessitated the relatively lower application rate of the CSS. Additionally, prior to their application, both amendment materials were also analyzed for nutrient and OM compositions after oven-drying and sieving through a 2-mm mesh (Table 3.1).

Table 3. 1: Mean chemical composition (standard deviation, sd) of the applied organic amendment materials, PLM and CSS; n = 3.

Parameter	pH	N	P	K	S	Ca	Mg	OM	OC	C/N ratio
		(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	
PLM	6.63	4.44	0.45	2.06	0.28	25.50	0.20	73.45	42.60	9.65
(sd)	(0.12)	(0.01)	(0.01)	(0.03)	(0.02)	(0.71)	(0.00)	(1.49)	(0.86)	(0.25)
CSS	6.61	3.33	0.56	0.79	0.35	10.70	1.05	40.45	23.49	7.40
(sd)	(0.02)	(0.57)	(0.01)	(0.18)	(0.01)	(0.42)	(0.07)	(0.28)	(0.17)	(0.65)

### 3.2.5 Tree growth and survival

To evaluate the effects of organic amendments on tree growth and survival, diameter and height of all planted trees as well as number of surviving trees were taken twice, 7-months (December, 2016) and 14-months (July, 2017), after planting. Tree height was measured from the soil to the apex of the tree crown using a tape measure, whilst basal stem diameter was taken at 10 cm above the soil surface with the aid of a veneer calliper. The survival of each tree species was expressed as a percentage by dividing the number of trees surviving by the initial number planted and multiplying by 100.

### 3.2.6 Statistical analyses

All statistical analyses were performed with IBM SPSS Statistics Version 25.0. The first study hypothesis, effect of topsoil stockpiling on soil properties, was statistically tested using the independent samples t-test ( $n = 3$ ), by comparing soil parameters (dependent variables) of STP and REF, at 95% confidence interval ( $\alpha = 0.05$ ). In addition, results of the analysed STP were compared mathematically with baseline soil data obtained by the Soil Research Institute of Ghana before mining operations at the site (Adu, 2012). In order to test the second hypothesis data on tree diameter (cm) and height (m) were first split into five groups based on tree species and then analysed separately using one-way ANOVA combined with LSD and Duncan post-hoc tests ( $\alpha = 0.05$ ) to determine OA treatment difference on tree growth.

### **3.3 Results**

#### **3.3.1 Effects of topsoil stockpiling on soil properties**

The results of this study revealed that stockpiling topsoil for a period of seven years at the Amoma Pit did not result in any significant adverse impact on the general topsoil properties, as compared with the REF (Table 2) and baseline soil data (Table 3.3). Soil organic matter content of the STP was very high and significantly greater than that of the REF; whilst the recorded mean pH in the STP was less acidic than the REF. Total N concentration in the TSP was moderate and significantly greater than the REF which was very low; however, P concentration was the same in both sites. Potassium concentrations were low at both sites, but was significantly greater in the REF than in the STP. Whilst Mg was moderate and statistically the same in the REF and TSP plots, Ca was high on both sites, but significantly greater in the REF plot.

The concentrations of acidic cations, H and Al, were not statistically different between treatments. Potassium and Ca concentrations were significantly greater in the REF plot, which contributed to a corresponding significantly greater calculated ECEC in the REF plot than in the TSP plot. On the contrary, the calculated percentage base saturation for the TSP treatment and the REF plot were statistically the same. Electrical conductivity, a measure of soil salinity (Brady and Weil, 2008), was also significantly greater in the REF plot than in the STP plot, although both were within the acceptable limits for vegetation establishment. The higher SOM concentration in the TSP plot contributed to greater concentration of organic carbon (OC). This, coupled with the relatively higher total N concentration in the TSP treatment, resulted in significantly lower carbon-nitrogen (C:N) ratio in the STP plot than the REF plot. The STP plot contained significantly greater percentage of silt and clay but significantly less sand content than the REF plot, thus yielding a texture of clay-loam for the STP plot and sandy-clay-loam for the REF plot. That different proportion of sand, silt and clay was associated with significantly higher bulk density in the TSP than in the REF plots.

A direct comparison of the results on soil properties with that of baseline soil data obtained by the Soil Research Institute of Ghana before mining operations (Adu, 2012) further confirmed topsoil did not generate any adverse impact on the soil properties since the soil values in the STP treatment plot were within the ranges of the baseline data (Table 3.3).

Table 3. 2: Soil chemical and physical characteristics of stockpiled topsoil (TSP) and soil from the reference site (REF).

Parameter	TSP	REF	P value
pH	6.2 (0.19)	5.5 (0.03)	
EC ( $\mu\text{S cm}^{-1}$ )	407.30 (80.64) a	228.30 (1.53) b	0.018
N (%)	0.11 (0.01) a	0.07 (0.002) b	0.001
P (%)	0.31 (0.001) a	0.31 (0.002) a	1.000
K ( $\text{Cmol}_c \text{ kg}^{-1}$ )	0.04 (0.00) b	0.08 (0.006) a	0.001
Mg ( $\text{Cmol}_c \text{ kg}^{-1}$ )	0.57 (0.63) a	0.67 (0.10) a	0.725
Ca ( $\text{Cmol}_c \text{ kg}^{-1}$ )	6.80 (1.09) b	9.80 (0.40) a	0.012
Na ( $\text{Cmol}_c \text{ kg}^{-1}$ )	0.71 (0.22) a	0.98 (0.01) a	0.099
H ( $\text{Cmol}_c \text{ kg}^{-1}$ )	0.65 (0.23) a	0.40 ( $\pm 0.04$ ) a	0.143
Al ( $\text{Cmol}_c \text{ kg}^{-1}$ )	0.34 (0.13) a	0.39 (0.08) a	0.435
ECEC ( $\text{Cmol}_c \text{ kg}^{-1}$ )	9.91 (0.24) b	12.32 (0.07) a	0.001
Base saturation (%)	82.69 (9.45) a	93.56 (0.37) a	0.118
OM (%)	6.20 (0.08) a	5.80 (0.01) b	0.003
OC (%)	3.60 (0.04) a	3.40 (0.01) b	0.002
C/N Ratio	32.29 (2.5) b	50.96 (1.2) a	0.001
bulk density ( $\text{g cm}^{-3}$ )	1.53 (0.03) a	1.32 (0.01) b	0.001
Sand (%)	40.75 (2.79) b	57.74 (0.45) a	0.001
Silt (%)	27.99 (2.16) a	16.08 (0.71) b	0.001
Clay (%)	31.26 (1.05) a	26.52 (0.41) b	0.001
Texture	Clay-loam	Sandy clay-loam	

Data were analysed using independent-samples *t*-test at  $\alpha = 0.05$ ;  $n = 3$ ; numbers are means with standard deviations in brackets; within a row, means followed by a different letter are significantly different.



Table 3. 3: Baseline soil properties before mining operations at NGGL.

Parameter	baseline data (mean)	Baseline data (range)	TSP	REF
pH	6.2	5.5 – 6.6	6.2	5.5
OM (%)	3.2	1.5 – 4.2	6.2	5.8
N (%)	0.17	0.08 – 0.39	0.11	0.07
ECEC	16.48	6.4 - 34	9.91	12.32
Base saturation (%)	98.5	98 - 99	82.69	92.89

### 3.3.2 Effects of organic amendment on tree survival

Seven months after tree planting and amendment application, there was no significant influence of OA on survival of trees in the five-timber species (Fig. 3.4).

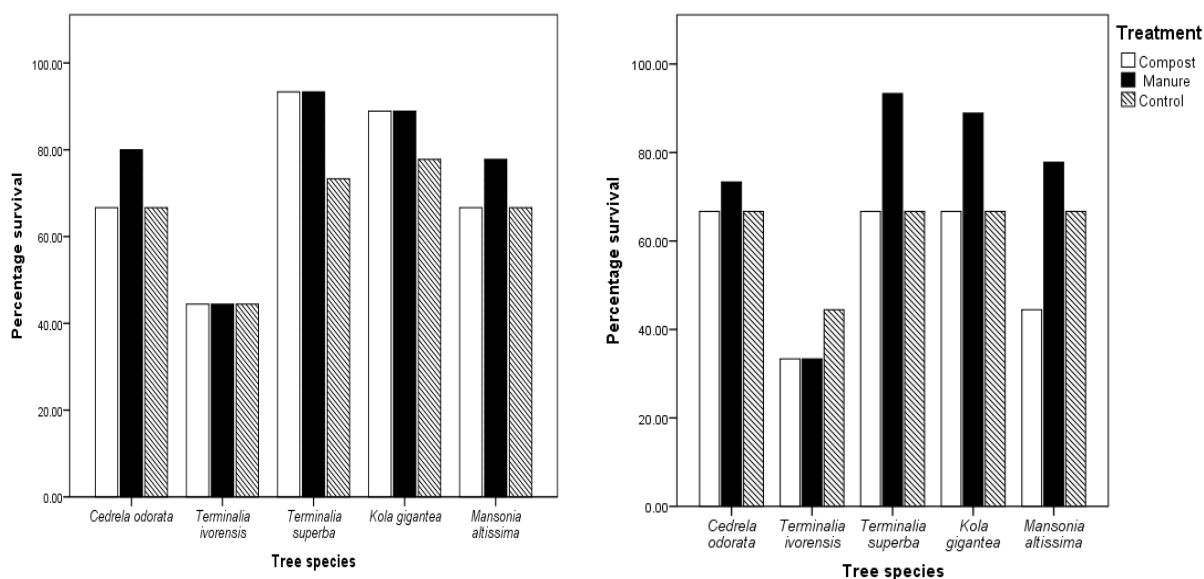


Figure 3. 4: Effect of OA on survival (%) of five forest tree species 7-months (left) and 14-months (right) after planting in a reclaimed mine site at NGGL.

*Terminalia superba* recorded the highest (93.3%) in both compost (CSS) and PLM, but 73.3% in control, followed by *K. gigantea* (88.9%) in both CSS and PLM, but 77.8% in control. Whereas survival of *C. odorata* (80.0 %) and *M. altissima* (77.8 %) differed slightly in poultry manure, the two species had the same survival of approximately 67.8 % in both compost and

control for the two species. *Terminalia ivorensis* exhibited the lowest survival rate and yielded the same value of 44.4% in all treatments.

In like manner, the second assessment did not record any significant changes in tree survival resulting from amendment application after 14 months (Fig. 4). In the PLM treatment, *C. odorata* and *T. ivorensis* exhibited further reductions in survival, 77.3% and 33.3% respectively. The other three species, *T. superba*, *K. gigantea* and *M. altissima* exhibited no further mortalities, and maintained their previous survival percentage of 93.3%, 88.9%, and 77.8% respectively (Fig. 3.4). The control exhibited a similar pattern with no further deaths recorded for *C. odorata*, *M. altissima* and *T. ivorensis*, thus maintaining their previous survival rate of 67.7% for both *C. odorata* and *M. altissima* and 44.4% for *T. ivorensis*. In contrast, *T. superba* and *K. gigantea* recorded further mortalities during this period, thereby reducing the survival to 66.7% for both species.

The compost treatment yielded the highest mortality among the species. Mortality occurred in three out of the five species in the period between the first and second assessments. There were sharp reductions in survival for *T. superba* and *K. gigantea*, both reducing to 66.7%; whereas *T. ivorensis* exhibited a moderate decline in survival to 33.3%. *Cedrela odorata* and *M. altissima* maintained their previous values of 66.7 and 44.4%, respectively, as there were no further mortalities.

### **3.3.3 Effects of OA on tree growth**

Seven months after planting, OA did not significantly influence either diameter (D) or height (H) growth among the five planted species, all p values  $\leq 0.05$ . *Cedrela odorata* exhibited the most growth in the PLM treatment followed by the CSS treatment with the control exhibiting the least growth (Fig. 3.5).

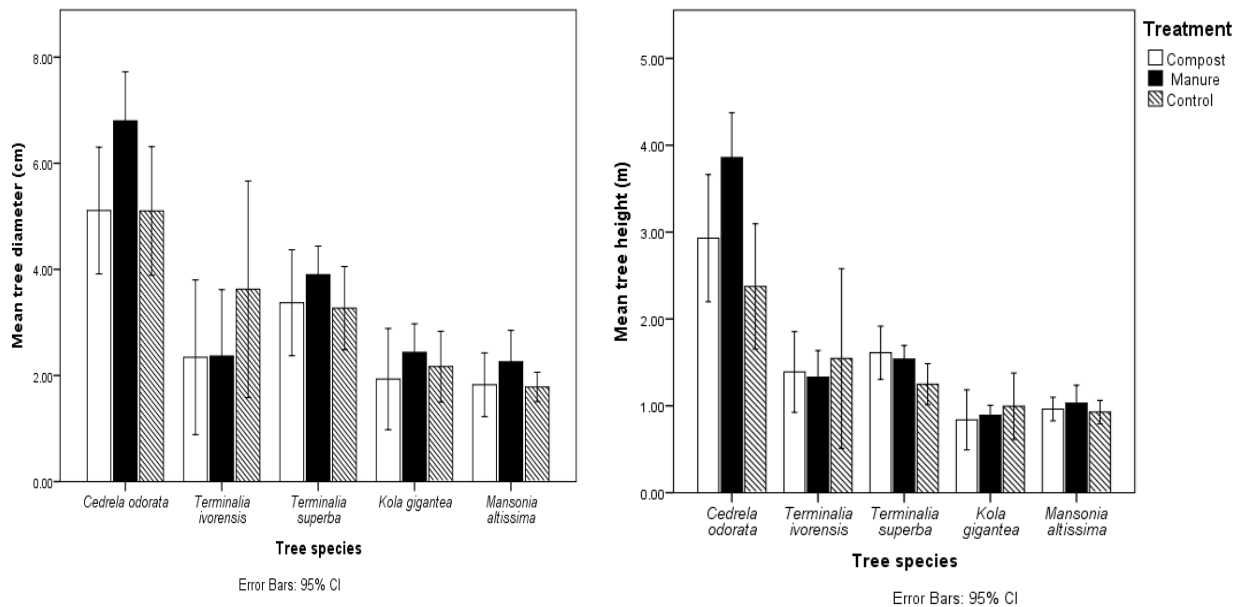


Figure 3. 5: Effect of organic amendment on diameter (left) and height (right) growth (mean values of n = 11, error bars represent 95% confidence interval) of five forest tree species seven months after planting and amendment application at NGGL.

Likewise, *T. superba* and *K. gigantea* showed a similar growth pattern, both exhibiting the most growth in the PLM treatment, followed by the CSS treatment and least growth in the control. Even though *T. ivorensis* displayed the most growth in the PLM treatment, this was followed by the control, with the CSS treatment exhibiting the least growth.

During the second growth assessment 14 months after planting and amendment application, OA did not affect diameter growth among any of the planted species (Fig. 3.6).

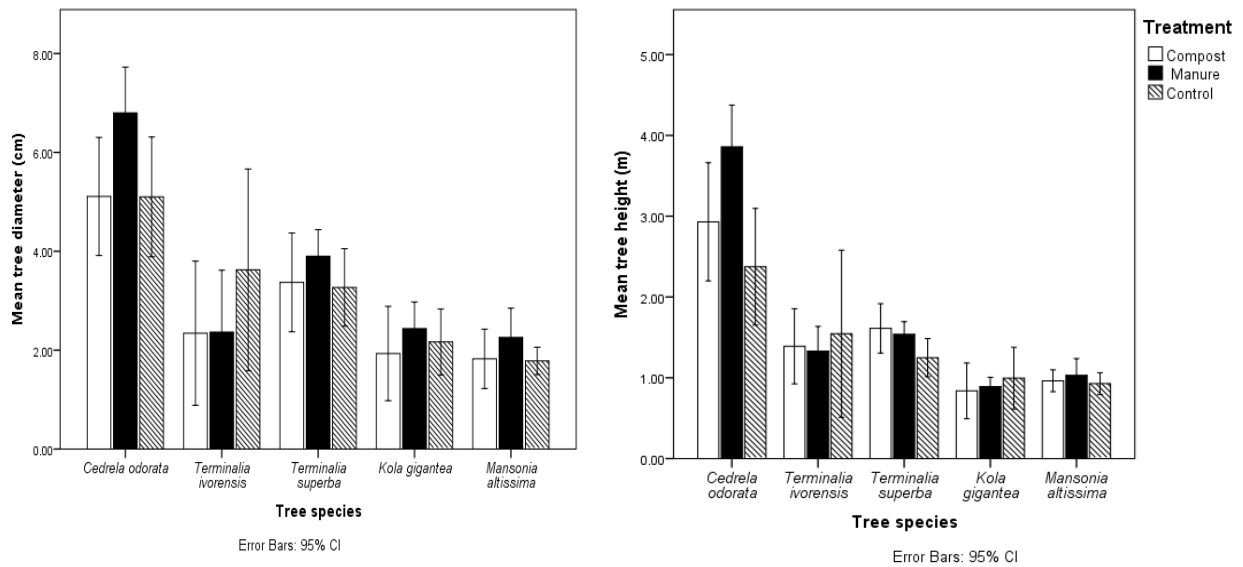


Figure 3. 6: Effect of OA on diameter (left) and height (right) growth (mean values of n = 11, error bars represent 95% confidence interval) of five forest tree species 14 months after planting and amendment application at NGGL.

With the exception of *T. ivorensis* which had the greatest diameter growth in the control, all the other species recorded greatest diameter growth in the PLM, although the values were not statistically different among OA treatment plots. *Cedrela odorata* exhibited a slightly significant greater height growth in the PLM treatment than the CSS treatment and the control. None of the other species exhibited significant dominance (Fig. 3.5 and 3.6). Tree species *C. odorata* and *M. altissima* displayed the greatest growth in the PLM treatment followed by the CSS treatment with the control displaying the least growth. *Terminalia ivorensis* and *K. gigantea* did not follow this pattern and had the greatest growth in the control followed by the CSS, with the PLM treatment yielding the least growth values. For *T. superba*, growth in height was greatest in the CSS treatment followed by the PLM treatment with the control recording the least.

Competition from herbaceous plants from the revegetation approach implemented by the company and lack of adequate weed control after tree planting were observed to be the main driving factors affecting tree survival and growth at the site (Fig. 3.7 and 3.8).



Figure 3. 7: Less competition, high survival (left), strong competition, low survival (right).



Figure 3. 8: Effect of competition on height growth of *T. superba* seven months after planting in PLM; less competition, fast growth (left = 0.96 m), strong competition, slow growth (right = 0.72 m).

### 3.4 Discussion

#### 3.4.1 Effects of topsoil stockpiling on soil properties

Contrary to our expectations and the first hypothesis, topsoil stockpiling during mining operation at the Amoma Pit did not cause significant adverse impacts on soil properties such as pH, nutrients, OM, EC, ECEC, and base saturation, compared to the REF soil. This finding contrasts with previous studies (Abdul-Kareem and McRae, 1984; Akala and Lal, 2000; CI, 2000; DOEC, 2005; Harris et al. 1989; Visser et al, 1984; Wright, 2002), that found topsoil stockpiling adversely affected SOM content, nutrients supply and pH following land

disturbance activities like mining (Reuter, 1997). These three soil parameters are considered the most important determinants for the suitability of a site for restoration (Bending et al., 1999).

This study, however, revealed that all three parameters were not adversely affected by stockpiling, when compared with the REF. According to DOEC (2005), while baseline data on soil that was obtained before mining operations started can be very valuable at the reclamation stage, the chemical and physical properties are often adversely affected by the mining operations. Nonetheless, a direct comparison between the TSP and a baseline soil data obtained by the Soil Research Institute of Ghana before mining operations (Adu, 2012) likewise showed stockpiling did not generate any adverse changes to soil properties. Further comparisons with guidelines from other studies, as far as reclaimed mine soils (Larney and Angers, 2012; Wall, 2014) and even agricultural soils (Brady and Weil, 2008) are concerned, again demonstrated the properties of the TSP were within the acceptable range for vegetation establishment.

The high SOM content of the STP was mainly attributed to the proper topsoil management (TSM) strategy implemented by NGGL both prior to mining operations and at re-application during reclamation. The company employed the double stripping topsoil management strategy (TMS) (Wright, 2002) with most of the vegetation biomass, including stumps and root of trees, salvaged and buried in the STP. This practice helped in the long-term preservation of the STP quality by generating more SOM, which corresponded to the OC content necessary for soil microbial activity in initiating carbon and nutrient cycling processes (Larney and Angers, 2012). In addition, prior to stockpiling the STP was covered with BGTs to control erosion (Nsiah and Schaaf, 2018) and seeded with deep-rooted perennial plants, which have been demonstrated to increase biological activities and restore soil structure into the deeper soil profile (Brady and Weil, 2008; Hamza and Anderson, 2005; Rai et al., 2014). Furthermore, the site being in a humid tropical climate with high temperature and moisture (NGGL, 2015) might have promoted continuous cycling of nutrients and OM accumulation from both above- and below-ground biomass of the perennial plants (Hazleton and Murphy, 2007; Wright, 2002; Brady and Weil, 2008). Moreover, the significantly higher SOM concentration in the STP compared with the REF was ascribed to the fact that there was no tillage or cultivation within the period of the stockpiling, which made the STP similar to a fallow land. In contrast, the REF was a cultivated cocoa farm. Therefore, the significantly lower SOM content at the REF site could be attributed to losses through erosion and crop harvesting as well as C oxidation to the atmosphere as carbon dioxide (Brady and Weil, 2008; Schlesinger, 1997; Six et al., 2002). Again, the high SOM concentration in STP was associated with

significantly greater N content in the STP compared with the REF. The lower SOM and N concentration in the REF soil resulted in a significantly greater C:N ratio compared to STP.

Despite the statistical difference in the recorded ECEC, the calculated BS for both sites was very high. This was anticipated since the pH values were near neutral, indicating the variable charge from SOM dominated the exchange sites (Hazleton and Murphy, 2007). The average percentage of sand, silt and clay correlated with the soil texture difference between the STP (clay-loam) and the REF (sandy-clay-loam). The difference in soil texture could be ascribed to more soil erosion at the REF which was a cultivated Cocoa farm compared to the STP, which behaved more like a fallow land that was well controlled from erosion during the stockpiling period. This is further supported by the fact that the REF contained lesser silt and clay contents than the STP, since silt and clay are known to be eroded preferentially by rainfall (CI, 2000; Rickson, 2006; Wright, 2002). The low bulk density at the REF, thus correlated with larger fraction of coarse sand particles resulting in larger macro pores compared with the TSP that had more aggregated fine clay particles with more small pores (Brady and Weil, 2008). Notwithstanding the differences, the recorded STP values for both texture (clay-loam) and bulk density, an indicator for soil compaction, were within the recommendation range ( $1.5 - 1.7 \text{ g cm}^{-3}$ ) for tree establishment on reclaimed soils (Rollet et al., 2015) as well as that of productive native soils (Brady and Weil, 2008).

Results on topsoil properties after seven years of stockpiling at NGGL were quite distinct from those of a study by Harris et al. (1989) who explored the effects of 3 to 252 months of topsoil stockpiling on microbial activity and physical properties. They found that older stockpiles had poor structure, high bulk density, decreased microbial biomass, lowered soil nitrogen, and decreased organic carbon. The observed decrease in SOM and changes in chemical properties following topsoil stockpiling has been attributed to oxidation reactions by soil microbes (Wells and Potter, 1986;) as well as methods of stripping and piling (Visser et al., 1984), which was properly controlled through the adopted topsoil management strategy at NGGL. The findings of this present study are supported by Rai et al. (2014) who reported less impact on nutrient cycling and microbial activity when plant cover can be maintained with roots extending throughout the depth of topsoil stockpile.

### **3.4.2 Effect of organic amendment on tree survival and growth**

Although the analysis of the STP revealed stockpiling had no adverse impacts on soil properties, i.e. there were no limiting conditions of the seven-year old stockpiled topsoil, the OA was applied in order to test the second hypothesis. Whilst application rates of OA of up to

100 tons per hectare have been recommended (SNIFFER, 2010), the rates are site-specific based on the properties of the amendment materials, such as C:N ratio, purpose of application and quality of in-situ material especially, pH, OM and nutrients, as well as the intended use of the land following application (Rollet et al., 2015). Analyses of both the PLM and the CSS revealed high nutrient and OM contents with low C:N ratios. This coupled with the good quality of the STP resulted in low application rates of the AMs, which were applied to planted trees only, and not evenly mixed with the entire substrate, as a way of ensuring the nutrient levels were not too excessive (Rollet et al., 2015) or phytotoxic (Darmody et al., 2009).

Although general survival of the planted tree species was not optimal in both assessment periods, this could not be attributed to the effect of the OA since treatments did not differ significantly in any of the individual tree species analyzed. In similar manner, both diameter and height of the same tree species planted within the same treatment plot showed OA amendment had no significant influence on tree growth. Hence, the hypothesis that amendment of the STP with OAs, CSS or PLM, will significantly promote survival and growth of planted trees was rejected. As discussed above, the lack of an OA effect on tree survival and growth was chiefly attributed to appropriate TSM strategy adopted by the company prior to the mining operations and re-application of same during reclamation. The practice generated optimum conditions of the STP especially the high SOM content, pH and nutrient levels favorable to plants, which have been demonstrated as the most important determinants of a disturbed site's suitability for restoration or improvement (Bending et al., 1999; Williamson and Johnson, 1990) following land disturbing activities. Another possibility could partly be ascribed to the low application rates of the AMs, which could not cause any further significant improvement to soil conditions and thereby promote the growth and survival of planted trees. This conforms to the findings of Chantigny et al. (1999) who emphasized that despite the fact that application of OM results in immediate increase in SOC, the increase is generally proportional to the amount of carbon applied, and in cases of high background levels, the changes in SOC may not be measurable or detectable following low or moderate application rates of amendment materials (Viaud et al., 2011).

The main cause of disparities in survival and growth of planted trees were observed to be attributed to the management practices for revegetation adopted by the company, rather than to the OA treatment. Although the final end land use on the waste rock dump was planned to be forestry, the standard revegetation practice being implemented by NGGL was to plant grasses as cover crops in the first year, as part of the slope stabilization activities, before planting the intended forest tree species in the second year. Whereas the practice was observed



to work excellent as far as soil stabilization and erosion control was concerned, with the exception of few areas with high concentrated run-off flows (Nsiah and Schaaf, 2018), a major problem of competition from herbaceous ground cover was observed to be the main cause of the low survival and wide growth disparities within same tree species planted on same treatment plots. At the beginning of planting season in the second year (April-May), most of the plots had already been invaded by very fast growing grasses and other herbaceous pioneer species. Vegetation at the site had to be manually cleared, in some plots twice, in order to pave way for planting the forest tree seedlings. However, because weed roots were already well established in the soil, the weeds regrew rapidly and overcrowded the planted trees, thus hindering their survival and subsequent growth.

The average survival recorded at the experimental site was observed to be higher than that of the general site that was being reclaimed by the company. This was due to the fact that the present study adopted circle weeding (twice) around trees on the experimental plots as part of weed control. The first circle weeding was carried out six weeks after planting (June, 2016) while the second was conducted seven months after planting (December 2016). The company on the other hand, undertook first general weed control, in the form of manual weeding with the aid of cutlasses, in August 2016, three months after tree planting, including that of the experimental plots. Weed control was practiced on the experimental plots three times, whereas it was practiced only once on the rest of the reclaimed site within the initial seven months after tree planting and before the major dry season in December. Thus, inadequate weed control resulted in more competition and less tree survival at the general reclamation site compared to that of the experimental plot.

Burger et. al. (2005) also have identified competition from herbaceous ground covers established to control erosion as one of the prevalent problems that have historically confronted reforestation and timber production in reclaimed mine sites in the United States of America. The authors proposed two approaches to overcome the historical challenge and to achieve effective revegetation success based on whether the end land use is forestry or agriculture; the forestry reclamation approach (FRA) and the grassland/agronomy reclamation approach (GRA)/(ARA). According to Burger et al. (2005) the GRA/ARA employs fast-growing agricultural grasses and legumes to achieve rapid and complete ground cover; whereas the FRA should adopt a slow-growing, non-competitive, tree-compatible ground cover that will lead to a lower-growing, less-vigorous, sparse groundcover that allows planted tree seedlings to survive and grow. The approach being implemented currently at NGGL was seen to conform to that of GRA, instead of FRA. While still focusing on the FRA, another strategy being

proposed by this study which is anticipated to help contribute to the survival and growth of planted trees is the simultaneous planting of the intended tree species and seeding of grasses and/or other cover crops during the first year. This is because, unlike the United States where the recommendation is originating from (West Virginia) which has temperate climate and plant diversity favoring slow-growing ground cover, that of the current study at NGGL (Ghana) is humid tropical climate associated with high temperatures and precipitation as well as high plant diversity and growth (NGGL, 2015). In addition, the TSP from tropical forest is known to retain a majority of seeds and roots (CI, 2000). That coupled with the optimum temperature and moisture conditions, stimulated sporadic regeneration of the stored seeds and roots of the less-recalcitrant pioneer species following the topsoil replacement. Moreover, the pioneer species were able to utilize the initial resources in the STP to initiate mineralization that ensured rapid growth of other herbaceous species, thereby contributing to the provision of a high SOM pool via net primary productivity (Larney and Angers, 2012) in all treatment plots that eventually neutralized any effects from the OMs.

### **3.5 Conclusions**

Contrary to the general assertion and belief about the adverse impact of stockpiling on soil properties, this study has demonstrated topsoil salvaging and stockpiling did not cause any significant adverse impacts on soil properties during NGGL's mine operation at the Amoma Pit, thus falsifying the first study hypothesis. This was mainly attributed to the proper TMS strategy implemented by NGGL which generated optimum soil conditions of the STP. The good substrate conditions provided by the STP and subsequent best reclamation management practices following replacement such as installation of BGTs, site scarification and seeding of cover crops (grasses) which were the same in all treatment plots, provided the required nutrients to initiate primary productivity that eventually nullified any potential beneficial effects of the organic amendment. Another possibility was partly ascribed to the low application rates of AMs. Consequently, amendment with the PLM and the CSS had no significant effect on the survival and growth of planted tree species during the reclamation process.

Competition from herbaceous ground cover that resulted from the company's revegetation approach of seeding cover crops in the first year and postponing planting of intended tree species until the second year, coupled with lack of adequate weed control were observed to be the main driving factors affecting survival and growth of planted trees at the site. Therefore, planting the intended forest tree species concurrently with the establishment of erosion and sediment control ground cover species in constituting the initial phase of the

revegetation process, coupled with adequate weed control are perceived to influence survival and growth of planted trees, rather than the current focus on application of the CSS as OA. Even so, a policy on topsoil salvaging and stockpiling and re-application of same for revegetation, as being implemented by NGGL, is recommended for all mining companies in Ghana as a best management practice. This will go a long way in promoting and guaranteeing responsible mining, thereby redeeming the negative image of the mining industry in Ghana.

### **3.6 Acknowledgements**

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## CHAPTER FOUR

### **Paper III: Subsoil amendment with poultry manure as topsoil substitute for promoting successful reclamation of degraded mine-sites in Ghana.**

Paul Kofi Nsiah and Wolfgang Schaaf

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#### **Abstract**

**Background:** Despite the key role topsoil plays in reclamation, there are situations where topsoil is in deficit or unavailable, especially, at the degraded and abandoned mine-sites in Ghana. The sites pose serious ecological and safety risks, underscoring the urgent need to finding alternative substrate for restoration. Hence, this study aimed at the feasibility of using amended-subsoil as topsoil substitute for reclamation. The hypothesis was that amendment of stockpiled-subsoil with poultry manure positively influences tree growth and ground vegetation cover (GVC) which promote better soil stabilization at degraded mine-sites. A graded waste-rock dump was covered with a 70 cm layer of the stockpiled subsoil at Newmont Ghana Gold Limited. Two experimental plots (24 × 15 m) were established with the treatments poultry manure (PLM 23 t ha<sup>-1</sup>) and control (no PLM), followed by seeding of Cowpea (*Vigna unguiculata*) and planting of potted-seedlings of five forest tree species. The Laser-point-quadrat method was used to estimate GVC, whereas erosion was visually observed. Diameter and height data of planted trees and surviving numbers were collected.

**Results:** There was significant increase in tree growth and in GVC, compared to the control. The manure provided sufficient nitrogen to overcome N immobilization and facilitated quicker and stronger vegetation growth that yielded superior soil stabilization.

**Conclusions:** The findings demonstrate the necessity of manure application in promoting successful restoration of the many degraded and abandoned mine-sites in Ghana to productive uses.

Key words: Ecosystem restoration, erosion control, ground vegetation cover, soil stabilization, stockpiled-subsoil, waste-rock dump reclamation.

## 4.1 Introduction

Mining is known to contribute significantly to the socio-economic growth and development of most economies, especially those in developing countries (UNGA, 2012) such as Ghana. Mining is basically about the extraction and further processing of minerals which directly aims at the removal of vegetation and topsoil which is the main substrate for plant growth (UNEP, 2000). Mining activities can cause severe adverse impacts on ecosystems such as destruction to soil and water resources, landscapes, vegetation, wildlife and habitats if appropriate measures are not maintained (CI, 2000; Hüttl and Weber, 2001). For instance, in Ghana presently, both so-called legal and illegal mining operations, popularly referred to as “galamsey” (gather the minerals and sell) have generated and continue to generate such severe adverse impacts on the ecosystems that most Ghanaians perceive the discovery of minerals and subsequent mining as curse.

The challenge then becomes how to find sustainable ways in exploiting the abundant minerals resources nature has endowed Ghana in a manner that protects the environment, to help erase the negative perception of mining by Ghanaians. According to UNGA (2012) mining serves as foundation for the sustenance and development of man offering the opportunity to catalyse broad-based economic development, reduce poverty and assist countries in meeting internationally agreed development goals, including the Millennium Development Goals, when managed effectively and properly.

Hüttl and Weber (2001) maintain that, even though large-scale surface mining represents an ecological disaster at the landscape level, ecological restoration of post-mining areas offers the rare opportunity to examine the development of ecosystems starting at “point zero”. Designing a comprehensive reclamation programme during the planning phase of a mining project, and implementing it concurrently throughout operations, has been demonstrated to minimize environmental damage, reduce future clean-up costs and decrease potential legal liability (CI, 2000; Wright, 2000). From an ecological perspective, land reclamation is defined as a process of supporting ‘the development of soils, vegetation, the wildlife, the water balance and water quality in order to allow future land uses such as agriculture or forestry (Bradshaw and Hüttl, 2001) after degradation. Conservation International (CI, 2000) believes mine site reclamation is synonymous with rehabilitation and defines the term as the restoration of mined land to its pre-mining conditions, or alteration to make it available for another productive use. Thus, land reclamation measures are needed to restore the degraded land for fruitful use at the end of the mining operation.



#### **4.1.1 The role of topsoil in mine reclamation**

Topsoil is defined as the upper darkened layer of natural soil that is enriched in organic matter and plant available nutrients and is typically a superior plant growth medium to the deeper subsoil layers (Darmody et al., 2009). Topsoil is universally recognized as vital in revegetating disturbed mine sites and in ecosystem health. This is because topsoil contains important resources for plant growth, for instance, native seeds and other plant propagules, soil biota such as fungi and bacteria, organic matter (OM) and plant available nutrients that aid in promoting the emergence and growth of pioneer and other planted species on newly reclaimed lands (CI, 2000; Nsiah & Schaaf, 2018; Reuter, 1997; Wright, 2002; Zipper et al., 2011). Best reclamation management practices (BRMPs) therefore require that topsoil is salvaged and stockpiled prior to mining and re-applied (Norman et al., 1997; NSE 2009; Skousen et al., 2011) as substrate for vegetation growth to promote site restoration. Subsequently, Newmont Ghana Gold Limited (NGGL) stockpiles all topsoil and subsoil separately to reconstruct the original layering of soil horizons for future restoration.

#### **4.1.2 Challenges on topsoil acquisition during mining operations**

Several studies have identified challenges on topsoil acquisition and storage such as unavailability at the site being mined especially at quarry sites (DOEC, 2005; Norman et al., 1997; Nsiah, 2012; CI, 2000; Zipper et al., 2011). Besides, where topsoil is available, there could be other potential challenges like contamination with plant pathogens and weed seeds (invasive species) that could defeat the restoration goal (DOEC, 2005; Wright, 2000) or potential topsoil deficit, such as is being perceived at NGGL. According to NGGL (2015) topsoil salvaged at the beginning of mining operation ranged between 8 to 20 cm, whereas subsoil depth was 120 to 150 cm. The company's standard practice for establishing vegetation on waste-rock dump is to replace 70 cm depth of the subsoil followed by 30 cm topsoil. This is perceived to generate potential topsoil deficit at the site, whilst subsoil will be in excess. Again, previous studies revealed the existence of many degraded and abandoned mine sites in Ghana where the topsoils were not salvaged and stockpiled prior to the mine operations (Nsiah, 2008; 2012). The sites pose serious ecological and safety risks and also serve as continuous sources of erosion and sedimentation to rivers and streams. All such degraded sites must therefore be restored to eliminate the risks and to make those lands available for productive use. Even though topsoil could be imported from elsewhere to restore the degraded sites, such practice has been shown to be associated with other challenges such as high transportation costs, whilst the topsoil exporting area is degraded to fix a problem elsewhere (Darmody et al.,

2009; Larney and Angers, 2012). Therefore, creation of alternative growth media for vegetation establishment in guaranteeing and promoting successful restoration of those degraded mine-sites is warranted.

#### **4.1.3 Alternative materials as topsoil substitute**

Some research studies propose that where little or no topsoil for revegetation exists, it may be necessary to amend, manufacture or import soils depending on the final land use and site conditions (Darmody et al., 2009; NSE 2009). Others have also demonstrated that alternative materials such as subsoil, overburden, waste-rock, etc., can be applied as topsoil substitutes for revegetation during reclamation (Darmody et al., 2009; DOEC, 2005; Nsiah, 2012; Zipper et al., 2011). In the United States, for instance, although Federal and State regulations require the natural soil existing at sites prior to mining (topsoil) be salvaged and stockpiled for revegetation, the rule is waived for proponents working in areas where it is difficult to save the topsoil and where operators can show that topsoil substitutes are as good or better for the post-mining land use as the original soil (Skousen et al., 2011). Again, CI (2000) report an instance where invasive species had dominated a stockpiled topsoil at the Ranger Uranium Mine in northern Australia rendering it unsuitable for site revegetation. Instead, waste rock was found suitable for revegetation, and it was used in place of the original topsoil. Other studies (Gerwin et al., 2010; Hüttl et al., 2014) demonstrated successful restoration of an open-cast mine in the Lusatian lignite-mining district in eastern Germany without the application of topsoil after extensive application of amendments like lime and mineral fertilizer.

One of the most important considerations for topsoil substitutes is to meet certain chemical and physical criteria, especially pH, texture and nutrients, in order to qualify as suitable substrate for vegetation growth (Skousen et al., 2011; Zipper et al., 2011). The authors further emphasize that the material should be easily weatherable. The topsoil substitutes may also require techniques or amendments to increase their organic matter and nutrient contents as well as to improve the physical properties for successful revegetation (Larney & Angers, 2012; Wright, 2000). Even though it could take 250 to 350 years for mine spoils to reach organic matter levels similar to adjacent undisturbed soils in Saskatchewan, organic amendments can speed up the recovery process by injecting large amounts of organic matter to initiate nutrient cycling and overcome soil physical limitations (Anderson, 1977; Salazar et al., 2009; Shipitalo and Bonta, 2008). Thus, whereas application of topsoil is key in successful revegetation, amendment of mine-spoil with manure and other organic materials has been

demonstrated to improve soil physical, chemical and biological properties together with improved plant growth on degraded lands (Edwards and Daniel, 1992; Larney & Angers, 2012; Nsiah, 2012; Rollet et al., 2015).

Baseline soil data obtained before mining operations started can be used to evaluate if the mining activity adversely affected chemical and physical soil properties (DOEC, 2005). Characterization of the topsoil substitute in terms of its physical and chemical properties is therefore essential to identify its suitability and the necessary remediation required for successful plant growth (DOEC, 2005; Skousen et al., 2011). Besides, the initial characterization serves as effective means of identifying risks and liabilities which can seriously affect site quality and the overall success and sustainability of site restoration (Hutchings, Sinnet, & Doick, 2014). Furthermore, through substrate characterization, future clean-up costs and potential legal liabilities can be avoided by preventing the environmental damage in the first place (CI, 2000). The assessment provides real baseline data to evaluate the overall success of reclamation measures.

Consequently, this study was aimed at the feasibility of using subsoil amended with poultry manure as topsoil substitute for restoration of degraded mine-sites in Ghana. The hypothesis was that amendment of stockpiled-subsoil (STS) with poultry manure positively influences growth of trees and ground vegetation cover which promote better soil stabilization at degraded mine-sites. The specific objectives were (a) to characterize the STS and evaluate its potentials as topsoil substitute in terms of pH, OM, nutrients, electrical conductivity (EC), effective cation exchange capacity (ECEC), base saturation (BS), texture, bulk density and heavy metal concentrations; and (b) to assess the effects of amendment of STS with poultry manure on tree growth and on the establishment of ground vegetation cover in stabilizing the site against soil erosion.

## **4.2. Material and Methods**

### **4.2.1 Description of Study location**

The study was carried out a waste-rock dump (WRD), generated from the Amoma Pit at NGGL Ahafo-south gold project, situated between latitudes 6°40', 7°15', North and longitudes 2°15', and 2°45' West, Kenyase in the Brong-Ahafo Region, Ghana (Fig. 4.1).



Figure 4. 1: The study location of NGGL, Ahafo-South project, Kenyase (Source: NGGL 2015).

The NGGL Ahafo-south project involves the development of four pits, being operated by the surface mining method, to produce and process approximately 7.5 Mt of ore annually. The site has a bi-modal rainfall pattern with the major rain beginning from mid-March to early July; and whereas the minor rain is from September to November with average annual rainfall of 1,232 mm (Nsiah & Schaaf, 2018). In general, March is the hottest month with an average temperature of 27.8°C and August as the coolest month with a mean temperature of 24.6°C. The soils have developed over weathered products of lower birimianphyllite and alluvial sediments within river and stream valleys and the floodplains of the Tano River. The soils are classified according to the USDA Soil Taxonomy and the FAO World Reference Base as Ultisols (Acrisols and Nitisols) on the uplands and Fluvents (Fluvisols) and Inceptisols

(Cambisols) in the lowlands (NGGL, 2015). Hall & Swaine, 1981) classified the area under the moist semi-deciduous ecological zone, northwest sub-type and is characterized by a three-storey structure with emergent tall trees often exceeding 50 m in height.

## 4.2 Methods

### 4.2.1 Design of experiment

A trial plot measuring 15 by 48 m was graded to form a 33 % slope followed by placement of a 70 cm layer of a seven-year old STP, without topsoil (Fig. 4.2). The STS was loosely placed on the waste-rock dump to avoid compaction and destruction to soil structure.



Figure 4. 2: The graded waste-rock dump (left); replacement of the STS on the graded rocks (right).

Prior to the application of manure and tree planting, the STS was characterized to determine its initial soil composition and potential heavy metal contamination, since heavy metal contamination has been associated with mining activities (Hazelton and Murphy, 2007). Six soil cores were randomly sampled to a depth of 30 cm with the help of soil auger, immediately after STS replacement in May, 2016. All six samples were mixed in a plastic bucket to make a composite sample. The content was transferred onto a clean plastic tray for further divisions and about 1 kg of the composite sample was placed in a brown paper bag (Motsara and Roy, 2008). Separate samples were taken with 100 cm<sup>3</sup> metal ring cores to a depth of four centimeters to determine bulk density. All samples were taken with three

replications following the same protocol and sent to the laboratory for analyses of physical and chemical soil properties, including heavy metal concentrations.

With the exception of samples used in determining soil bulk density, all the other samples were air-dried and sieved through a 2-mm mesh. Soil pH and EC were measured with the aid of a multi-parameter PC 300 series electrode in 5:1 soil to water suspension (Motsara and Roy, 2008). The volumetric Sodium tetraphenyl boron method was used in determining exchangeable sodium (Na) and potassium (K), after dry ashing digestion of the soil sample and analyzing with a Jenway flame photometer model PFP7, whereas magnesium (Mg) and calcium (Ca) were estimated by means of a Spectrophotometer (BSS 280 G), after extraction by ammonium acetate (Motsara & Roy 2008). Exchangeable acidity due to hydrogen (H) and aluminium (Al) was extracted using 0.1N KCl solution and the filtrate titrated with 0.05N NaOH to a colourless end point. Exchangeable acidity (Al and H) was determined by adding 4mls of 3N to the extract and titrated with 0.05N HCl to a pink end point. Total phosphorus (P) was estimated by the blue complex molybdate and thiophosphate method in acid solution and analyzed using Buck Scientific Spectrophotometer (BSS) model 280 G. Total nitrogen was determined by the Kjeldahl method (Motsara and Roy, 2008).

The ECEC was calculated by the summation of exchangeable bases and acidity; whereas BS was estimated as the percentage of the base cations (Na, K, Mg and Ca) of ECEC (Hazleton and Murphy, 2007). Organic matter from both manure and STS samples was determined by the loss of weight on ignition method as described by Motsara and Roy (2008) with the help of a muffle furnace model L9/S, at 550 °C for four hours. Total heavy metal concentrations in terms of AS, Pb, Cu, Ni, Cr, Zn, Mn and Cd was extracted by means of acid digestion using a mixture of 9:4 nitric: perchloric acid and filtered through Whatman 1 acid-washed filter paper. Heavy metal analysis was carried out by Atomic Absorption Spectrophotometric model AA 220 (Motsara and Roy, 2008). Particle size analysis was carried out through the hydrometer method (Bouyoucos, 1927) and textural class was determined using the textural triangle diagram according to the United States Department of Agriculture soil texture classification system. Bulk density was determined using undisturbed soil cores collected in a 100 cm<sup>3</sup> metal ring core and weight was determined after oven-drying (Brady and Weil, 2008).

Having characterized the site, the experimental plot was split into two equal parts of 24 m × 15m, with the treatments, poultry layer manure (PLM) and no amendment (control). Single large application of organic amendment has been proven to accelerate initial revegetation success and lead to self-sustaining net primary productivity (Larney and Angers, 2012).

Consequently, 1,000 kg of the PLM was applied on its treatment plot at one time, yielding application rate of 23 tons (dry weight) per hectare, which was evenly spread on the surface manually and incorporated within the top 10 cm with the aid of shovel. This was followed by the implementation of other BRMPs such as seeding of Cowpea (*Vigna unguiculata*) as cover crop and installation of “York” mat biological geotextiles on both treatment plots for erosion and sediment control (Nsiah and Schaaf, 2018). The cowpea was seeded at 30 cm intervals in irregular lines with 3-bean seed per hole. Analyses of the PLM (Table 4.1) showed it contained high nutrient contents, particularly total N and OM contents, with low C:N ratios.

Table 4. 1: Chemical composition of the applied poultry manure, numbers are means with standard deviations in brackets N = 3.

<b>Parameter</b>	pH	N	P	K	S	Ca	Mg	OM	OC	CN
		(%)	(%)	(mg <sup>-kg</sup> )	(%)	(mg <sup>-kg</sup> )	(mg <sup>-kg</sup> )	(%)	(%)	ratio
<b>Mean</b>	6.63	4.44	0.45	2.06	0.28	25.50	0.20	73.45	42.60	9.65
<b>S.D.</b>	0.12	0.01	0.01	0.03	0.02	0.71	0.00	1.49	0.86	0.25

In each treatment plot, 11 potted-seedlings each of the indigenous tree species *Terminalia superba*, *Terminalia ivorensis* and *Khaya anthotica* as well as exotic species *Cedrela odorata* and *Senna siamea*, were planted at a distance of 3m by 3m in irregular lines, in June, 2016. The indigenous species were selected because they are native to the region whilst *C. odorata* and *S. siamea*, despite being exotic species, were chosen because of their adaptability to the ecological site as well as their relatively fast growth rate. Besides, the selected tree species are rated as having high trade values in both the domestic and the international timber market. Furthermore, their seedlings were readily available at a no cost from the NGGL nursery stock, whereas a few of them were bought at a relatively low cost from the University of Energy and Natural Resources nursery department in Sunyani.

#### 4.2.2 Data collection

The Laser-point-quadrat method (BLM, 1996) was used to determine the ground vegetation cover (GVC) by demarcating 1m by 2m (2 m<sup>2</sup>) grid quadrats, yielding a total of 216 monitoring quadrat points per treatment plot. Four weeks after amendment application, tree



planting and seeding of the cover crop, observations were made on “hits” and “misses” along a walking transect with the aid of a measuring tape (Fig. 4.3).

Figure 4. 3: Observations of hits and misses using Laser-point-quadrat at NGGL; left = PLM; right = control; four weeks after the experimental start (07/06/ 2016 - 05/07/2016).

A “hit” was recorded if the laser beam made a strike on any vegetation; while the beam hitting a bare soil was taken as a “miss”. Thus, only one hit or one miss was recorded in each of the 216 quadrats of each treatment plot. The percentage GVC for each treatment plot was calculated by dividing the number of hits in that plot by the total number of monitoring quadrat points and multiplying by 100. The combined effect of manure application and GVC on soil stabilizing against erosion was visually observed.

Six months after the experimental start (December, 2016), diameter and height data of all planted trees and the number of surviving trees were collected. The tape measure was used to estimate tree height, which was measured from the soil surface to the tip of the tree canopy, whereas basal stem diameter was measured at 10 cm above the soil surface using a veneer calliper. Percentage survival of the individual tree species was calculated by dividing the number of trees surviving by the total number of that species initially planted, and multiplying the product by 100.

#### 4.2.3 Data analysis

All data were analyzed using IBM SPSS Statistics Version 25.0. Descriptive statistics (mean and standard deviation) were performed to determine the initial soil properties of the STS. The study hypothesis was tested using one-way ANOVA ( $\alpha = 0.05$ ) to verify whether



treatment significantly affected individual tree growth, with PLM as factor and height and diameter as the dependent variables. Besides, data on tree growth and GVC were presented in bar graphs, with the aid of the legacy dialogs, for visual comparisons.

### 4.3 Results

Results on the characterization of the STS used for the experiment, as depicted in Table 4.2, revealed the soil was sandy loam with a moderate bulk density according to Brady and Weil (2008) and a near neutral pH. Nutrient contents with respect to exchangeable K and total N concentrations were very low whilst that of phosphorus (P), magnesium (Mg) and calcium (Ca) were moderate. The OM/organic carbon (OC) content was moderate which combined with the very low N content to yield a high C:N ratio. Whereas total Na was low, the other exchangeable bases, Mg and Ca, were moderate. Exchangeable acidity was very low which promoted a high base saturation.

Table 4. 2: Chemical and physical properties of the stockpiled-subsoil (STS), numbers are means with standard deviations in brackets; N = 3.

Parameter	Value
pH	6.60 (0.10)
EC ( $\mu\text{S cm}^{-1}$ )	159.92 (1.21)
N (%)	0.04 (0.002)
P (%)	0.29 (0.006)
K ( $\text{Cmol}_c \text{ kg}^{-1}$ )	0.05 (0.01)
Na ( $\text{Cmol}_c \text{ kg}^{-1}$ )	0.77 (0.07)
Mg ( $\text{Cmol}_c \text{ kg}^{-1}$ )	4.10 (0.26)
Ca ( $\text{Cmol}_c \text{ kg}^{-1}$ )	7.03 (0.20)
H ( $\text{Cmol}_c \text{ kg}^{-1}$ )	0.40 (0.08)
Al ( $\text{Cmol}_c \text{ kg}^{-1}$ )	0.36 (0.04)
ECEC ( $\text{Cmol}_c \text{ kg}^{-1}$ )	12.71 (0.43)
Base saturation (%)	94.02 (0.23)
OM (%)	3.83 (0.01)

OC (%)	2.22 (0.01)
C/N ratio	62.63 (3.20)
Bulk density (g cm <sup>-3</sup> )	1.30 (0.01)
Sand (%)	66.58 (0.88)
Silt (%)	22.33 (1.11)
Clay (%)	11.09 (0.40)
Texture	Sandy loam

The concentrations of heavy metals such as arsenic, lead, copper, nickel, chromium, zinc, manganese, and cadmium in the STS and that of the PLM (Table 4.3) were all within acceptable limits, when compared with USEPA (1994) and EU standards (Alloway et al., 2000).

Table 4. 3: Heavy metal concentrations of the STS and the PLM against USEPA and EU standards. N = 3; Numbers are means with standard deviations in brackets; n.a. = not available.

Heavy metal	STS	PLM	USEPA (Non-residential soil)	EU (Agric. Soil)
As (mg kg <sup>-1</sup> )	1.95 (0.21)	1.45 (0.07)	20	40
Pb (mg kg <sup>-1</sup> )	2.10 (0.42)	2.70 (0.57)	600	200
Cu (mg kg <sup>-1</sup> )	45.15 (1.49)	36.35 (0.21)	600	140
Ni (mg kg <sup>-1</sup> )	298.00 (60.81)	213.00 (1.41)	2400	n.a
Cr (mg kg <sup>-1</sup> )	0.40 (0.00)	0.40 (0.00)	100	150
Zn (mg kg <sup>-1</sup> )	101.75 (0.92)	7.75 (0.21)	1500	300
Mn (mg kg <sup>-1</sup> )	602.0 (140.01)	18.50 (0.71)	n.a	3000
Cd (mg kg <sup>-1</sup> )	4.85 (1.06)	1.50 (0.14)	100	n.a

Four weeks after the experimental setup (June 7 – July 5, 2016), there was a positive response of GVC to poultry manure amendment, which was almost four times higher (79.8 %) at the PLM, compared to the control (23.3 %) (Fig. 4.4 & 4.5).



Figure 4. 4: Effect of poultry manure on GVC, four weeks after the experimental start; left = control (slow and poor vegetation growth with lesser ground cover); right = manure treatment (fast and strong vegetation growth with greater ground cover).

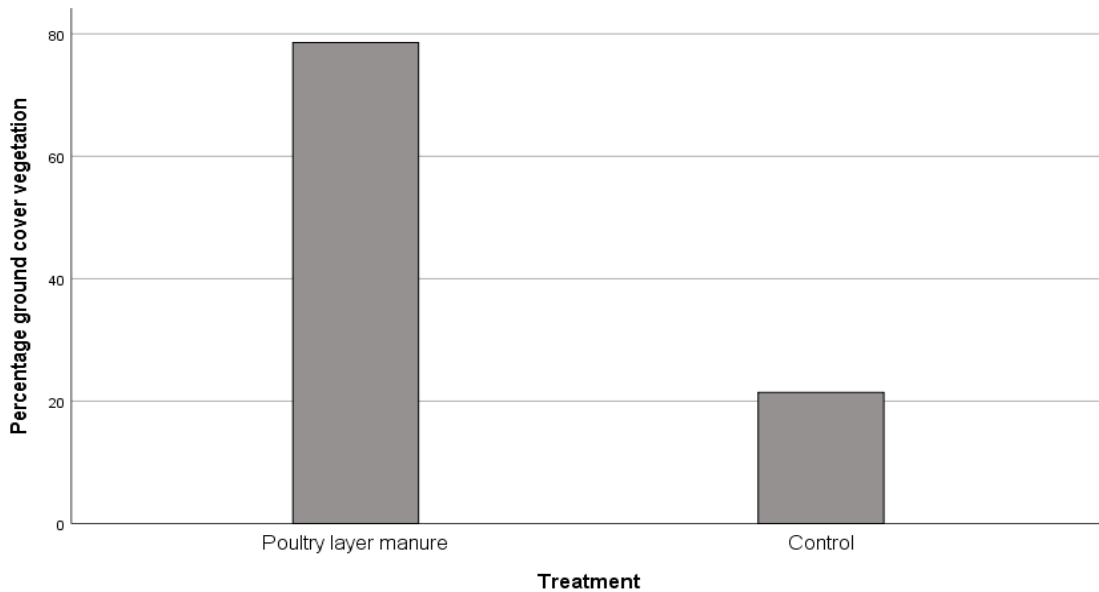


Figure 4. 5: Effect of poultry manure on ground vegetation cover during restoration at NGGL.

Visual observations on the site revealed the presence of sheet and rill erosion on the control plot whereas the manure-treatment plot showed much superior soil stabilization (Fig. 4.6).



Figure 4. 6: Effect of poultry manure on soil erosion; left = manure treatment (no observable signs of erosion, superior soil stabilization,) right = control (presence of sheet and rill erosion, poor soil stabilization).

Amendment of the STS with the PLM resulted in significantly greater ( $p < 0.05$ ) diameter (Fig. 4.7) and height (Fig. 4.8) growth for the three species *K. anthotica*, *T. superba* and *C. odorata* as well as height growth of *T. ivorensis* after six months of planting and amendment application. There was, however, no amendment effect on both diameter and height growth of *S. siamea* and diameter of *T. ivorensis*.

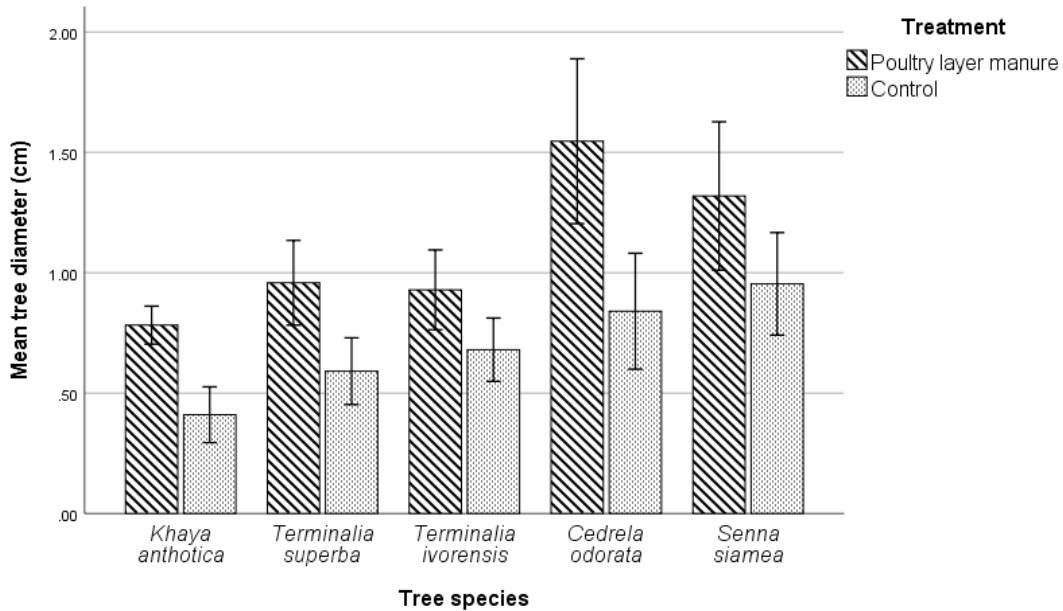


Figure 4. 7: Effect of manure on diameter growth of five forest-tree species after six months of planting on a waste-rock dump at NGGL. N = 11; Error bars represent 95% confidence interval.

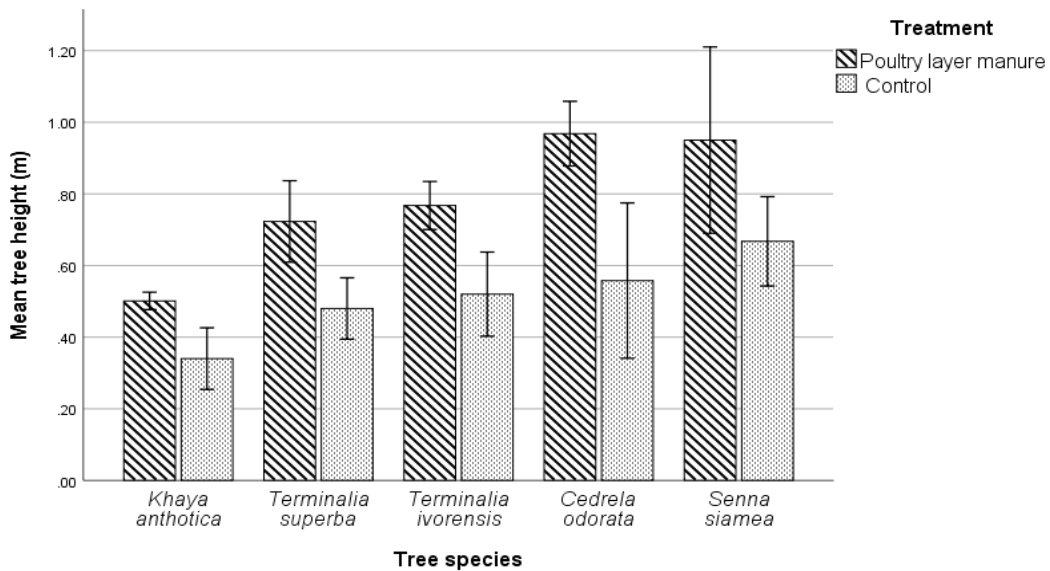


Figure 4. 8: Effect of manure on height growth of five forest-tree species after six months of planting on a waste-rock dump at NGGL. N = 11; Error bars represent 95% confidence interval.

There was no clear difference regarding survival of the planted trees among treatment plots (Fig. 4.9). *Cedrela odorata* recorded the highest survival of 100 % in PLM, but moderate survival of 72.7 % in control, whilst *T. superba* recorded 90.9 % in both treatments. *Khaya anthotica* and *S. siamea* yielded the same survival value of 81.8 % in PLM with the control recording 63.6 and 72.7 %, respectively. *Terminalia ivorensis* recorded the least survival in both treatment plots (72.7 % in PLM and 54.5 % in control).

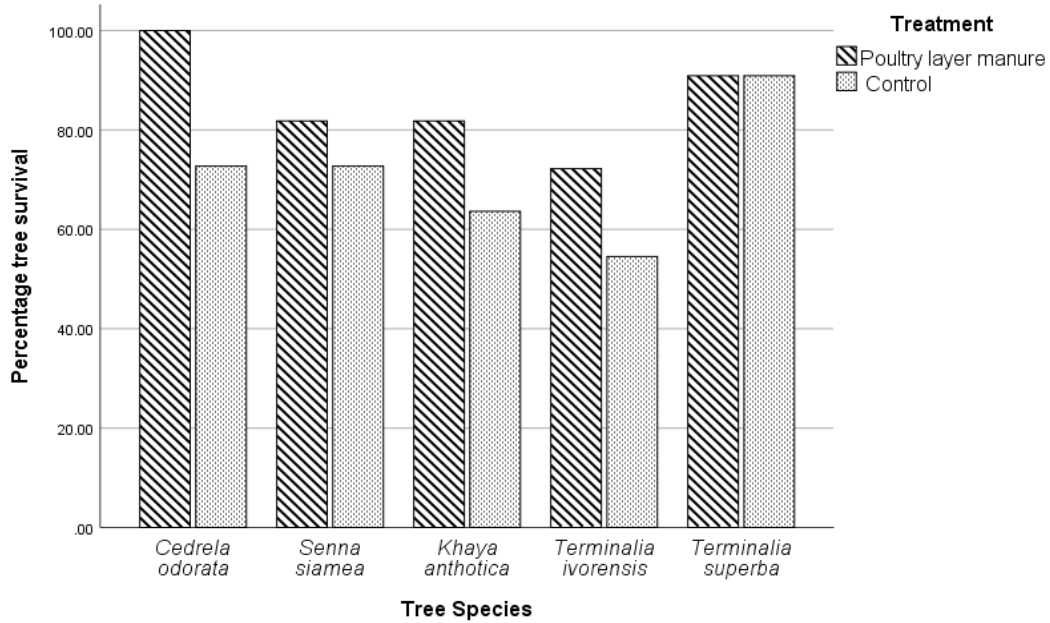


Figure 4. 9: Effect of poultry manure on survival (%) of five forest-tree species after six months of planting on a waste-rock dump at NGGL. N = 11.

#### 4.4 Discussion

Relying on natural processes alone in building the needed biotic and abiotic resources in restoring disturbed mine-sites could take several decades, if not centuries (Anderson, 1977). A major challenge during the initial phases of restoring degraded mine-sites in Ghana is how to stabilize the soil against the highly erosive tropical rains and runoff, especially on graded-slopes, which are characteristic of surface mining (Norman et al., 1997; Nsiah, 2012; Nsiah and Schaaf, 2018; Wright, 2000). Therefore, beginning from ground zero, the application of the manure-amended subsoil material in this study was to reduce such long periods by serving as substrate for establishing vegetation that would hasten the development of an initial stable ecosystem (Hüttel and Weber, 2001). Both the topsoil and the subsoil were separately stockpiled during the initial stages of mining activities at the Amoma Pit in 2009 to reconstruct the original

layering of soil horizons during future restoration of the site. Unlike our previous study (Nsiah and Schaaf, 2019) that conformed to this goal of reconstructing the original soil layering at the site by replacing the stockpiled topsoil (STP) on top of the subsoil as substrate for vegetation establishment, this current study replaced only the subsoil on the WRD in order to help overcome the potential topsoil deficit at the site. Again, the applied subsoil is similar in characteristics to those found at the degraded and abandoned mine-sites in Ghana where the topsoils were destroyed during the mining activities, which suggest the findings from this study could be transferred to those sites.

Some researchers have demonstrated that generally, the chemical and physical properties, such as pH, nutrients, organic matter, ECEC, bulk density, texture as well as heavy metal concentrations of the soil removed prior to mining are often adversely affected by the mining operations and pose constraints for vegetation establishment (DOEC, 2005; Hutchings, Sinnet, Doick, 2006; Vega et al., 2005). This study therefore deemed it very necessary to characterize the STS to identify its quality and any necessary remediation before vegetation establishment. The results of the analyses of the STS revealed a near neutral soil pH and conductivity which were considered optimum for vegetation establishment on disturbed mine sites (Larney & Angers, 2012; Skousen et al., 2011; Wall, 2014) as well as on arable lands (Brady and Weil, 2008; Rollet et al., 2015). The content of OM was considered moderate, compared to our previous study (Nsiah and Schaaf, 2019) where OM contents of both the STP and that of a fresh topsoil sampled from a nearby un-mined site as reference, were both high. Thus, high SOM content is seen as an intrinsic characteristic of the site, which is a typical humid-tropical ecosystem with high temperatures and precipitation which facilitate fast accumulation of biomass into OM (Brady and Weil, 2008). Calcium and Mg were moderate, with very low exchangeable acidity and high base saturation, which suggested the soil had great potentials in adsorbing and releasing the cations for plant growth (Brady and Weil, 2008). Total N content was very low and resulted in a high C:N ratio, indicating presence of N immobilization, which was considered as the main chemical limitation as far the ability of the STS for vegetation growth was concerned.

A major source of heavy metals in the environment has been attributed to the release and spread of metals as a result of human activity such as mining (Hazleton and Murphy, 2007). Again organic amendments are often negatively viewed as waste products with undesirable features, particularly heavy metals, which can potentially be transported to surface and ground waters or bio-accumulate in plants (Larney and Angers, 2012; Nicholson et al., 1999). Subsequently, both the STS and the PLM were assessed for heavy metal concentrations, in

order to evaluate any risk of potential contamination at the reclaimed site (SNIFFER, 2010). The results showed the concentrations of all the measured heavy metals were within the acceptable limits, when compared with USEPA (1994) and EU standards (Alloway et al., 2000) suggesting both the PLM and the mining activity had no adverse impacts on metal contamination and posed no ecological and human health risks to the site.

In terms of the physical properties, The STS contained high sand and a low clay contents thereby yielding a sandy-loam texture with a relatively lower bulk density, compared to the STP used in our previous study (Nsiah and Schaaf, 2019) that had a relatively higher bulk density and a texture of sandy-clay-loam. The low bulk density of the STS in this study was chiefly attributed to the fact that the subsoil material was loosely placed on the waste-rock dump which lessened the effect on compaction. The relatively lower bulk density and sandy-loam texture implied the STS had a higher soil erodibility and therefore needed more extensive soil stabilization measures against erosion in allowing the vegetation to establish and grow, compared the STP used in the previous study (Nsiah & Schaaf, 2019).

Soil organic matter content, nutrients supply and pH have been described as the most important determinants for the suitability of a site for restoration (Bending et al., 1999; Gregorich et al., 1994) following disturbances such as mining. Whereas pH of the STS was optimum with moderate OM content; nutrient, especially total N content, was very low and implied N immobilization. Nonetheless, results of the analyzed manure showed high total N and OC contents, generating a low C:N ratio, which was seen to be ideal for the release of N for plant growth (Brady and Weil, 2008). The poultry manure was selected as the amendment material for this study because it is produced in abundance by the poultry industry in Ghana which is considered as a waste product, and can therefore be obtained at a no cost. Poultry manure also serves as an abundant source of OM and nutrients needed for sustained plant growth (Edwards and Daniel, 1992; Nsiah, 2012). Thus, the amendment of the STS with PM is considered an appropriate and economic measure in disposing of poultry manure as a by-product, whilst promoting successful restoration of the degraded and abandoned mine-lands in Ghana for productive uses.

Even though application rates of OAs of up to 100 tons per hectare have been recommended (SNIFFER, 2010), the rates are site-specific based on the properties of the AMs, such as C:N ratio, purpose of application and quality of in-situ material especially, pH, OM and nutrients, as well as the intended land use (Rollet et al., 2015). Due to N immobilization of the STS, a high rate of 23 tons PLM per hectare was applied, which was evenly incorporated within the top 10 cm of soil. This approach was contrary to that of our previous study (Nsiah



and Schaaf, 2019) where a low application rate of the PLM (1.1 ton per hectare) was applied to the planted trees only, due to the good quality of the STP.

The results revealed a significant influence of the PLM on both diameter and height growth of the planted trees as well as on GVC that promoted better soil stabilization on the manure treatment plot, compared to the control; thereby confirming the study hypothesis. This was attributed to the manure-amendment with the STS that supplied sufficient N and additionally increased SOM thereby promoting microbial activity and mineralization (Larney and Angers, 2012) that overcame the N deficiency. Thus, the conversion of the organic N in the manure to plant available form and additional increase in SOC were responsible for the significant increase in tree growth and more GVC that ensured better site stabilization in developing an initial stable ecosystem. This was speculated because the results of the characterization of the STS indicated N immobilization as the principal chemical limitation to vegetation growth.

The findings from this study is in support of a proclamation by Seaker and Sopper (1988) that the restoration of disturbed mine sites depends on the reestablishment of vegetation that can thrive and sustain itself, provided appropriate levels of organic C and N contents are available. The results further confirm that of previous studies where the use of OAs were demonstrated to speed up the reclamation process by introducing large amounts of organic matter to initiate nutrient cycling and to overcome soil physical constraints (Salazar et al., 2009; Shipitalo and Bonta, 2008). The outcome of the study further confirms a statement by Rollet et al. (2015) that organic materials, along with other mineral soil-forming materials, such as subsoil, can be valuable additions in creating soil forming materials to improve and restore habitats. The advantage of using organic amendments over mineral fertilizers has been attributed to the fact that organic amendments add both nutrients and organic matter, resulting in more improvement of soil physical, chemical and biological properties (Larney and Angers, 2012). Addition of biosolids was more effective at enhancing properties related to soil quality and fertility on reclaimed copper mine tailings sites in British Columbia than the traditional use of inorganic fertilizer (Gardner et al., 2010).

Our previous study (Nsiah and Schaaf, 2019) discussed certain limitations concerning the use of Bermuda grass (*Cynodon dactylon*) as cover crop which was the company's standard reclamation practice. The slow rate of establishment after transplanting the grass seedlings from the nursery stock promoted sporadic regeneration of herbaceous pioneer weed species that competed with the planted tree species thereby hindering their survival and subsequent growth. To overcome these limitations, the Cowpea was selected in this study instead of the

Bermuda grass, due to the capacity of former in fixing atmospheric nitrogen as well as its relatively fast growth, long taproot and dense canopy cover for erosion control and weed suppression (Brady and Weil, 2008; Clark, 2007). Although the results of the present study confirmed such characteristics as fast growth rate and dense canopy cover of Cowpea that aided in better erosion and sediment control, these effects could only be realized on the manure treatment plot. There was stunted growth and less GVC on the control plot that resulted in sheet and rill erosion. This was mainly ascribed to the lack of plant available N for the establishment of greater GVC essential for soil stabilization against erosion at degraded mine-sites (Larney & Angers, 2012; Nsiah & Schaaf, 2018).

Manure contributions in decreasing soil erosion as observed in this study is line with other studies that demonstrated application of compost decreased erosion by 86 % compared to bare soils, and allowed quicker establishment of ground vegetation cover (Demars and Long, 1998; Risse and Faucette, 2015). The combined positive effect of the PLM and the York mat BGTs on erosion control (Nsiah and Schaaf, 2018), as witnessed in this study, also confirms that of a study by Bhattarai et al. (2011) who maintain their field experiments indicated that a 50–50 mixture of compost and mulch provided the best erosion control measures as compared to using either the compost or the mulch blanket alone. The achievement of better soil stabilization on the erosion-susceptible subsoil against the highly erosive forces of tropical rains and run-off, as revealed in this research, is contrary to a study by Hüttl et al. (2014) that witnessed massive sheet and gully erosion during first years of developing initial ecosystem at a Lusatian lignite mine North-eastern Germany, due mainly to lack of vegetation cover. Thus, beginning from ground zero, the manure-amended subsoil promoted the establishment of quicker and stronger vegetation that offered superior soil stabilization, which was crucial in developing an initial stable ecosystem at the WRD, within a relatively short time period.

#### **4.5 Conclusions**

The study has demonstrated the potentials of amending subsoil with poultry manure as topsoil substitute for reclamation of degraded mine-sites in Ghana, as well as other humid tropical climates with similar characteristics as found in the study area. Implementation of BRMPs such as seeding of fast-growing cover crops and installation of BGTs on the manure-amended subsoil yielded superior soil stabilization against erosion which further promoted the development of an initial-stable ecosystem, within a relatively short-time period. The findings highlight the necessity of using poultry manure as organic amendment in safeguarding successful reclamation of the many degraded and abandoned mine-sites in Ghana. This can go

a long way in promoting public acceptability of mining as a developmental land use activity, rather than as a curse. We recommend further studies about the long-term effects of one-time manure application in building biotic and abiotic resources in continuing the successional processes that would lead to a self-sustaining ecosystem at degraded mine-sites.

#### 4.6 Acknowledgements

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## CHAPTER FIVE

### **Summary and general conclusions, implications for practice and recommendations for future research**

#### **5.1 Summary and general conclusions**

Notwithstanding the vital contributions of the mining industry to the socio-economic growth and development of Ghana, mining operations have generated and continue to generate such severe adverse impacts on the environment that most Ghanaians perceive mineral discovery and subsequent mining as curse. Designing a comprehensive reclamation programme during the planning phase of a mining project, and implementing it concurrently throughout operations, is believed to minimize environmental damage, reduce future clean-up costs and decrease potential legal liabilities. Although Regulation (23) of the Ghana Environmental Assessment Regulation 1999, (L.I. 1652) requires large-scale mine proponents to have plans for reclamation, the principal factor contributing to numerous environmental degradation during mining operations in Ghana has been attributed to the failure in adopting best reclamation management practices (BRMPs) during mine operations. The key limitations during the reclamation process include: (a) stabilization of graded mine-slopes against the erosive forces of rain and runoff; (b) topsoil stockpiling and its usage for future reclamation; and (c) characterization of alternative materials and subsequent amendment as topsoil substitutes for vegetation establishment in situations where it is difficult to obtain topsoil.

Consequently, this thesis aims to help find solutions to the identified problems on mine land reclamation through the proper implementation of the omitted best practices in order to ensure successful reclamation of degraded mine sites in Ghana. With this in mind, three broad goals were pursued: (a) to investigate the role of biological geotextiles in protecting graded-mine slopes against erosion and sedimentation; (b) to examine the effects of organic amendments on topsoil stockpile as substrate for vegetation establishment; and (c) to explore the feasibility of stockpiled-subsoil amendment with poultry manure as topsoil substitute for revegetation, during the initial stages of reclaiming disturbed mine-sites. To achieve these broad goals, three kinds of field studies, each directed at one of the goals, were carried out at an active surface gold mine-site of Newmont Ghana Gold Limited (NGGL) Ahafo-south project, in the Brong-Ahafo Region.

Soil erosion is a significant environmental impact of surface mining affecting the initial establishment of vegetation on graded mine slopes, especially in tropical countries such as



Ghana. The first study was therefore targeted at the first goal by investigating the potentials of biological geotextiles in erosion and sediment control during reclamation. The hypothesis was that (a) gully formation in some reclaimed areas following application of YM BGTs is due to the flexibility of YM and that biological geotextile constructed from relatively rigid plant parts, like the stems of the elephant grass plant (EP), will be more effective in erosion and sediment control compared to YM. Six experimental plots, each measuring 14 \* 1 m, were established on a 33% WRD filled with a 70 cm depth of STS at the Amoma Pit. The STS was preferred to the STP because of its high sand and low clay contents that implied it was more susceptible to soil erosion and could therefore provide better evaluation on the performance of the selected BGTs against erosion and sedimentation. Two kinds of biological geotextiles constructed from two local plants; the Elephant grass plant (EP) (*Pennisetum purpureum*) and the paper mulberry plant (*Broussonetia papyrifera*) York mat and elephant grass mat, were used with bare ground as control in a randomized block design with two replicates each. Data collected on sediment yield was expressed as a percentage from the mean total sediment yield.

With a total precipitation of 306 mm in the period April 18, to July 4, 2016, the results showed both elephant grass mat and York mat significantly ( $p < 0.05$ ) reduced soil loss by 56.6% and 97.3%, respectively, compared to the control. Thus, both mats acted as cover and protected the highly erodible graded mine slope against the erosive forces of tropical rain and runoff and allowed vegetation to establish and grow through them. The relatively high performance of York mat was mainly attributed to its more fibers that provided more surface cover (70%) as well as flexibility of the fibers which enabled the mat to absorb more water during rainfall thus increasing its weight. This increase in weight promoted better drapability, with better erosion and sediment control. Against the study hypothesis, the study observed that the gully formations usually found at some reclaimed sites following BGTs installation were primarily due to high concentrated runoff flows from the top of reclaiming benches, which were so strong that the mats were not able to resist, with time delays between completion of earthworks, geotextile placement, and seeding of plants as predisposing factors.

Topsoil is a valuable resource and acknowledged as the most critical and key component in any successful revegetation following mining activities. It is, however, generally believed that topsoil stockpiling has adverse impacts on soil properties and that stockpiled topsoil would require some organic amendments to promote plant growth. Hence, the second study was directed at evaluating the effects of stockpiling on topsoil properties and that of organic amendment on tree growth, during the reclamation process. The hypothesis was that (a) topsoil stockpiling as practiced at NGGL has adverse impacts on soil properties and (b)

amending stockpiled topsoil with organic materials, CSS and PLM, promotes the survival and growth of planted trees. A WRD measuring 36 by 45 m was graded and covered with a 70 cm layer of a seven-year old STS followed by that of a 30 cm layer of STP. The STP was assessed for physical and chemical soil properties and compared with that of a fresh-soil sampled from a nearby un-mined site as reference. This was followed by the planting of potted-seedlings of five forest tree species; *Terminalia superba*, *Terminalia ivorensis*, *Mansonia altissima*, *Kola gigantea*, and *Cedrela odorata* and application of 1 kg and 0.5 kg (dry weight) of the PLM and the CSS respectively, per tree. Diameter and height data of planted trees and surviving numbers were collected twice (seven months and 14 months after planting) to determine tree growth and survival.

The results revealed topsoil stockpiling did not cause any significant adverse impacts on soil properties during NGGL's mine operation at the Amoma Pit. One-way ANOVA combined with LSD and Duncan post-hoc tests ( $\alpha = 0.05$ ) also indicated no significant influence of OAs on tree growth, thus falsifying the study hypothesis. The non-adverse impact of stockpiling on soil properties was chiefly attributed to the proper TSM strategy implemented by NGGL, especially burying of the vegetation biomass, including stumps and root of trees, with the soil and planting of deep-rooted perennial plants on the stockpiled, which promoted continuous cycling of nutrients within the stockpiling period thereby generated optimum soil conditions of the TSP. The good substrate conditions provided by the TSP and subsequent best reclamation management practices following replacement such as installation of BGTs, site scarification, and seeding of cover crops (grasses) which were the same in all treatment plots, provided the required nutrients to initiate primary productivity that eventually nullified any potential beneficial effects of the organic amendment.

Competition from herbaceous ground cover that resulted from the company's revegetation approach of seeding cover crops in the first year and postponing planting of intended tree species until the second year, coupled with lack of adequate weed control were observed to be the main driving factors affecting survival and growth of planted trees at the site, rather than the application of OA. Contrary to the general assertion and belief about the detrimental impacts of stockpiling on soil properties thereby demanding OAs to promote vegetation establishment, the study demonstrated that adoption of BRMPs in salvaging and stockpiling the topsoil during mining operations can help preserve the soil quality for a long term, without the need for OAs.

Even though topsoil plays significant role in establishing vegetation at disturbed mine sites, there are situations where topsoil is in deficit or unavailable, especially, at the degraded

and abandoned mine-sites in Ghana. The sites pose serious ecological and safety risks, underscoring the urgent need to finding alternative substrate for restoration. Hence, the third and last study was directed at the third goal by setting up experimental plot to explore the feasibility of STS as topsoil substitute for establishing vegetation during reclamation. The hypothesis was that amendment of STP with PM positively influences growth of trees and ground vegetation cover, which promote better soil stabilization at degraded mine-sites. A different portion of the WRD at the Amoma Pit was graded and covered with a 70 cm layer of a seven-year old STP. The subsoil was analyzed for physical and chemical soil properties including heavy metal contents. After the site characterization, two experimental plots (24 × 15 m) were established with the treatments PLM (23 t ha<sup>-1</sup>) and control (no PLM), followed by seeding of Cowpea (*Vigna unguiculata*) as cover crop and planting of potted-seedlings of five forest tree species in each plot. Four weeks from the experimental start, the Laser-point-quadrat method was used to estimate GVC, whereas soil erosion was visually observed. Diameter and height data of all planted trees and number of surviving trees were collected to determine tree growth and survival six months after the experiment.

Characterization of the STS revealed mining operations at NGGL did not cause chemical contamination to the soil. Again, there was no physical limitation, as properties such as bulk density and texture were optimum for establishing vegetation on disturbed mine soils and also on arable lands. Chemical soil properties such as pH, ECEC, base saturation OM and heavy metal concentrations were all optimum for vegetation establishment. The chief chemical limitation was the very low nitrogen content. The results showed positive response of GVC to the OA which was almost four times higher (79.8 %) at the amended plot, compared to control (23.3 %). Similarly, there was a significantly greater ( $p < 0.05$ ) diameter and height growth of trees, compared to the control. The manure provided sufficient nitrogen to overcome N immobilization and facilitated quicker and stronger vegetation growth that yielded superior soil stabilization, thereby supporting the study hypothesis. The study underscored the necessity of using poultry manure as OA in safeguarding successful reclamation of the many degraded and abandoned mine-sites in Ghana.

The outcome of the study highlights the necessity of implementing BRMPs in protecting the environment and securing successful reclamation during mine operation. The major BRMPs to be considered include topsoil and subsoil salvaging and stockpiling, installation of BGTs to control erosion and sedimentation, and application of organic amendments in safeguarding successful reclamation of the many degraded and abandoned mine-sites in Ghana. The adoption of the findings of this study in the reclamation of both the

so-called “legal” and illegal (galamsey) degraded mine mine-sites in Ghana is seen to protect public health, safety and the environment. This will promote the sustainable management of the nation’s mineral resources by guaranteeing a balance between mining the minerals for full the economic and social benefits that mining promises and a proper way of ensuring the environment or ecosystem is protected. The achievement of this will further contribute to Ghanaians’ acceptability of mining as a developmental land use activity, rather than as a curse.

## **5.2 Implications for practice**

The following implications for practice were made from the study:

- Salvaging and stockpiling the subsoil separately from the topsoil during mining operations can help overcome potential topsoil deficits during future reclamation.
- In contrast to studies reporting detrimental impacts of stockpiling on soil properties that demands application of organic amendments, implementation of proper topsoil management strategies can help preserve its quality such that no amendment would be required.
- Installation of BGTs constructed from some selected local plants in Ghana can help protect the graded mine slopes against the high erosive forces of the tropical rains and allow vegetation to establish and grow.
- However, stronger soil stabilization techniques, such as installation of temporary slope-drains, would be required to overcome rill and gully formations resulting from concentrated runoff flows at reclaimed mine-sites, besides BGTs application.
- Planting grasses as cover crops in the first year as part of the soil stabilization activities by deferring planting of the intended forest tree species in the second year promotes the establishment of fast herbaceous ground cover that can out-compete the planted tree species and thwart the entire reclamation success.
- Inadequate weed control will result in high competition that can significantly hinder the survival and growth of planted tree species, especially in areas where topsoil is applied as the substrate for revegetation.
- Amending stockpiled-subsoil with poultry manure can be used to substitute the topsoil for successful vegetation establishment in situations where it is difficult to obtain topsoil.

- Seeding fast-growing cover crops (Cowpea) in combination with BGTs installation on manure-amended subsoil promotes superior soil stabilization against erosion, that can accelerate the development of an initially stable-ecosystem, within a relatively short-time period.

### 5.3 Recommendations for future research

Based on the findings from the study, the following recommendations are made to help improve mine reclamation in Ghana:

- A policy on the adoption of best practices on salvaging and stockpiling the topsoil and re-application of same for revegetation, as being implemented by NGGL, must be in place for all mining companies in Ghana.
- Moreover, the entire reclamation programme must always be planned and coordinated in a manner that allows all earthworks to be completed at the end of the dry season in mid-March to give way for BGTs placement and plant seeding at the onset of the major rains. This is seen to significantly reduce the vulnerability of the newly reclaimed site, beginning from ground zero, to erosion and promote reclamation success.

Moreover, future research should be directed towards:

- The installation of temporary slope-drains in overcoming rill and gully formations that result from high concentrated runoff flows at reclaimed mine-sites.
- Comparing the effects of simultaneous planting of the intended forest tree species and seeding of ground cover species during the first year, to the current practice of deferring tree planting to the second year. This is important, particularly, where the end land use is forestry.
- Verifying whether the 100 cm depth of the replaced substrate on the WRD, as being implemented, is sufficient to provide adequate stability to the long rooting system of the planted forest tree species.
- Determining whether the 3 by 3 m planting distance recommended by the Ghana EPA can provide sufficient space to accommodate the broad canopies of the planted native tree species.
- Evaluating the long-term effects of one-time manure application with stockpiled-subsoil in building biotic and abiotic resources for a self-sustaining ecosystem.

- Evaluating the proper application rates of manure to avoid nutrient losses as well as the long-term effects of one-time manure application with stockpiled-subsoil in building biotic and abiotic resources for a self-sustaining ecosystem.

The study findings are being recommended for the successful reclamation of the many degraded and abandoned mine-sites in Ghana to protect public health, safety and the environment which would in turn promote responsible mining. Above all, general guidelines on reclamation completion criteria and performance standards in determining when reclamation is deemed successful for possible bond release must be in place in Ghana.