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Chemical and mineralogical properties of post-mining sites in two gold mining concessions in Ghana

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Abstract

Mining companies adopt different post-mining management practices to rehabilitate mined sites to enhance environmental management and sustainability. The study assessed the chemical and mineralogical properties of some post-mining land management options from two gold mines in the Western Region of Ghana. Samples of waste rock (WR), mine tailings (MTs), mine soils and un-mined soils were analysed for soil pH, cation exchange capacity (CEC), exchangeable cations, soil organic carbon (SOC), total nitrogen (Ntotal), concentrations of some heavy metals (HMs) and mineralogy by ICP-AES and X-ray diffraction techniques. The results revealed pH values of 4.2-4.6 in un-mined soils and 4.6-5.4 in mine soils. The MTs and WR were alkaline due to CaCO3 (4.8-5.8 g kg-1). Virtually all the samples contained kaolinite, muscovite and quartz. The MTs contained ankerite, bobierrite, clinoclase and greenalite, which were not present in the WR. These minerals were most probably neo-formed out of the chemical constituents of the tailings and contamination during the disposal. Mine soils from three-year-old reclaimed mine site planted with oil palm had substantial SOC and Ntotal contents among all the post-mining sites which also reflected slightly on the CEC status. This showed the influence of soil management practices such as mulching, cover cropping with Pueraria phaseoloides, erosion control and fertiliser application. The HMs contents in the mine tailings occurred in the order of Pb > As > Cd and revealed relatively higher contents in the abandoned MTs compared to reclaimed ones but they were all in the range of those in uncontaminated soils elsewhere.

Keywords: *Heavy metals; Soil Minerals; Mine soils and tailings; Reclamation; Soil organic carbon; Waste rock*

INTRODUCTION

The enactment of Surface Mining Control and Reclamation Act (SMCRA) by the US government in 1977 (Torbert and Burger, 2000) spurred reclamation in many states, eventually making it a global phenomenon. The Act stipulates the timely restoration of mine lands to pre-mine or better conditions (Torbert and Burger, 2000).

According to the Society for Ecological Restoration (SER), restoration is "the intentional alteration of a site to establish a defined indigenous ecosystem to ultimately emulate the structure, functioning, diversity, and dynamics of the specified ecosystem" (SERIS and Policy Working Group, 2004). Bradshaw (1996) argues that restoration is either not feasible or unrealistic as far as the biotic and abiotic components of an ecosystem are concerned. Thus, the terms "restoration *sensu stricto*" and "restoration *sensu lato"* have been suggested by Aronsod *et al.* (1993). The former refers to the SER definition whereas the latter denotes a restoration that arrests degradation and redirects an ecosystem towards one that is presumed to have existed before disturbance (Aronsod *et al.*, 1993). Amidst these propositions, the term "rehabilitation" was suggested and is defined as "the action of restoring a thing to a previous condition", to represent a mitigated but imperfect condition (Bradshaw, 1996). Currently, the term "reclamation" has been widely used and is also described as the "making of land fit for cultivation", referring to a return to a proper state (Bradshaw, 1996). Environmental impact assessments required by all projects according to the OECD recommends the mitigation of both potential and actual environmental impacts of projects (OECD, 1992; Morgan, 2012).

Within the context of mining, reclamation is the return of mine wastelands to some form of beneficial use (Cooke and Johnson, 2002), with an embedded safety factor (SERIS and Policy Working Group, 2004). According to Miao *et al.* (2000), mine land reclamation involves four main steps: (1) land reconstruction and resurfacing; (2) soil toxicity remediation; (3) irrigation engineering, where necessary; and (4) biological restoration and management. The last three are most critical and dictate plant establishment, biological recolonisation, soil organic matter accumulation, and eventually, soil development (Bradshaw, 1996; Miao *et al.*, 2000).

Ghana has a long history of gold mining and is the second largest African gold producer after South Africa (Ayee *et al.*, 2011). As in many countries of the world, the reclamation of mined lands in Ghana became obligatory following the review of Environmental Impact Assessment Regulations (L.I.1652) in 1992 (Acquah, 1995). Consequently, many mining companies undertook reclamation projects to protect the environment. Several post-mining conditions exist in every mining concession but vary with the type of ore exploited, geochemistry and the method of exploitation. Irrespective of the post-mining condition, unique management strategies are required to mitigate the environmental impacts of mineral extraction. In a gold mine, for instance, the existing post-mining conditions affect the environment during drilling and blasting of ore-containing rocks. In addition, the waste rocks and mine tailings used or reclamation alter the pre-mine soils. The concern of this paper is that the mine soils that are eventually used to support plant growth for human consumption need to be handled in a safe manner. Often mine spoils are prepared to support plant growth and establishment (Ussiri and Lal, 2005; Obade and Lal, 2013). During mining, top- and subsoils are stockpiled for subsequent replacement on backfilled mine pits. The mine sites normally are re-vegetated as part of the reclamation process generally are done with and without amendments depending on the chemical and mineralogical properties of the mine soils. For instance, the mine soils are characterised by low soil organic carbon (SOC), total nitrogen contents (Shrestha and Lal, 2007; Neina *et al.*, 2017), because of significant amounts of rock fragments from blasted rocks. Additionally, the impact of heavy duty vehicles may result in high bulk density and could influence soil structure. Shrestha and Lal (2007) observed unfavourable pH conditions ranging between high and low pH due to the type of regolith (overburden on top of the bedrock) or the geology of the mine itself.

Depending on the mineral extracted and the method employed in mining, different post-mining conditions exist. These pose different environmental challenges and dictate management strategies employed. For most gold mining sites, one may find waste rock (WR), mine tailings (MTs) and mine soils. Waste rock is a product of drilling and blasting of ore-containing rocks whose composition depends on site geology and host rocks (Hitch *et al.*, 2010) and is often used to backfill mined-out pits. The amount of WR generated varies with mine geology (Norgate and Haque, 2012) and is estimated using the strip ratio. A higher strip ratio produces a substantial amount of WR which is found to be higher in gold production than in other metals due to the relatively low grades encountered in gold production (Hitch *et al.*, 2010; Norgate and Haque, 2012). Mine tailings are by-products of milled ore obtained after metal complexation with cyanide which is held up in a pond-like disposal facility. The MTs may have high heavy metal contents (Ernst, 1988; Lan *et al.*, 1998) but this depends on the ore geochemistry. Mine soils are obtained when mine spoils are prepared to support plant growth and establishment (Ussiri and Lal, 2005; Obade and Lal, 2013) through backfilling of mine pits, topsoil replacement and re-vegetation with and without soil amendments. The depth of the soil material may depend on legal requirements which are based on the post-mining land use. These conditions require proper management to avoid "pollution havens" that lead to permanent environmental damage (Cohen, 1996; Tienhaara, 2006). Previous research revealed that reclamation may create pre-mine soil conditions with time (Barnhisel and Gray, 2000; Shrestha and Lal, 2006), especially after proper re-vegetation (Biemelt *et al.*, 2005; Neina *et al.*, 2017) because reclaimed mine soils have been identified to have high potentials to sequester SOC and improve soil conditions (Shrestha and Lal, 2006). However, this mostly depends on specific post-mining management practices employed and the target end land uses. For example, post-mining management practices such as topsoil salvaging, replacement, and re-vegetation (Harris *et al.*, 1996; Anderson *et al.*, 2008), application of N and P fertilisers (Obade and Lal, 2013), efficient use of organic amendments, and improved crop rotations (Liu *et al.*, 2011; Obade and Lal, 2013) are reportedly employed to improve mine soil environments. These practices have all been found to increase the SOC and microbial biomass contents that subsequently reduced soil bulk density (Anderson *et al.*, 2008; Liu *et al.*, 2011).

Most of these studies focused either solely on mine soils or on MTs which do not necessary create a link between the inherent geochemistry and post-mining conditions and their implications for environmental management and sustainability. This study assessed the chemical and mineralogical properties of these post-mining sites at Bogoso Gold Limited and Abosso Goldfields - Damang Gold Mine in the Western Region of Ghana.

MATERIALS AND METHODS

Description of study sites and sampling

The study areas were (1) Bogoso Gold Limited (BGL) located on coordinates 5°34'26.62"N, 2°47.00"W and situated in the Prestea-Huni Valley District and (2) Abosso Goldfields Limited - Damang Gold Mine (AGL-DGM) (5°21'46.55"N, 1°56'47.68"W) both in the Wassa West District. The geology of AGL-DGM is underlain by Tarkwaian sediments and is the only deposit of its kind, located on the eastern side of the Ashanti Belt in southwest Ghana (Oberthür *et al.*, 1995). That of BGL lies on the edge of West African Craton and is underlain by the Precambrian metasediments of the Birimian system, and the Tarkwaian system (conglomerates, quartzites and phyllites). The concession also contain Sulfide ores occurring in association with quartz veins, with auriferous arsenopyrite as a major host of gold (Oberthür *et al.*, 1995). The soils of the AGL-DGM concession belong to the Juaso/Mawso/Pamasua soil association described by the Soil Research Institute (1993). They are classified as Lithic Leptosols, Ferric Acrisols, and Dystric Fluvisols whereas those of the BGL are Acrisols, Fluvisols and Lixisols (Soil Research Institute, 1993) according to IUSS Working Group WRB (2014). The climate for both concessions is humid tropical with a bimodal rainfall regime, averaging 1800 mm per annum. The average temperature and relative humidity are 27ºC and 86%, respectively. The pre-mine land uses of both concessions were wildlife, farming, small-scale artisanal mining (mostly illegal) popularly known as *galamsey*, residential purposes, and forests (AGL, 2002; Duncan *et al.*, 2009).

At each concession, only available post-mining sites were sampled. The description of the specific sites sampled is presented in Table 1. At the AGL-DGM, seven different sites were sampled including a native forest (AGL-UN-F30); a WR dump (AGL-WR-0); mine soils from a six-year-old reclaimed mine site under *Leucaena* forest (AGL-RLF-6); mine soils from a six-year-old reclaimed mine site used as a mixed-crop farm (AGL-RMCF-6) of cocoyam, cassava and plantain; mine soils from a three-year-old reclaimed mine site under oil palm cultivation intercropped with pineapple (AGL-BF-OP3); tailings from a three-year-old reclaimed MTs planted with oil palm and *Pueraria phaseoloides* (Roxb.) Benth. legume cover (AGL-RMT-OP3); and tailings from a two-year-old abandoned MTs site (AGL-ABMT-2). Only three post-mining sites were obtained at BGL including a freshly backfilled site yet to be re-vegetated (BGL-FBF-0); a mine site reclaimed with *Acacia mangium* Wild. (BGL-RAF-3) and an un-mined forest (BGL-UN-F30) to serve as a control. To sample the sites, an area of 30 m × 30 m was marked out at each site and five (5) independent samples were randomly taken at 0-30 cm and 0-20 cm depths which were limited by the new mine soil depth after reclamation. For instance, at the reclaimed sites of AGL-DGM, the topsoil was so shallow and limited by the WR that had been used to backfill the site prior to re-vegetation. The samples were not composited but were used as replicates.

Sample analysis

The samples were air-dried, crushed, and passed through a 2-mm sieve. Soil pH was measured in a soil-water ratio of 1:2.5. Soil organic carbon content was determined by the Walkley and Black method (1934), total nitrogen (N_{total}) by Kjeldahl method while cation exchange capacity (CEC) and exchangeable cations were extracted with 1M NH_4OAc solution, buffered to pH 7 followed by measurement on an Inductively-coupled Plasma Atomic Emission Spectroscopy (ICP-AES) (Varian VISTA, Varian Inc., Melbourne, Australia). Calcium carbonate content was determined (for samples with high pH) following procedures outlined by van Reeuwijk (2002).

The samples were finely ground, homogenised and bulked to obtain powder samples for X-ray diffraction (XRD) to identify the minerals present. This was performed using a Philips PANanalytical

X'Pert XRD System, Oregon, USA (Cu-Kα radiation, scan time 1 s per 0.02° 2-theta). The minerals were identified by comparing d-spacing with standard reference XRD patterns according to the Joint Committee on Powder Diffraction Standards. The aim was to analyse as many heavy metals in the MTs as possible. Unfortunately, due to unforeseen circumstances, only one sample each of reclaimed and abandoned MTs was analysed for arsenic (As), cadmium (Cd) and lead (Pb) contents. Although, the authors are aware that this data set is inadequate to draw convincing conclusions, the results for both MTs highlight the real situation. Incidentally, these are the most common heavy metals identified by US EPA (1995). The extraction was done using aqua regia followed by measurement on an ICP-AES.

TABLE 1. A description of the post-mining sites sampled at the mine concessions.

Post-mining sites	**Sampling depth (cm)**	**Site description**
Abosso Goldfields Limited - Damang Gold Mine		
AGL-UN-F30	30	Unmined forest comprising old cocoa trees and native forest species, > 30 m high, > 30 years old; Sandy texture, yellowish brown (10YR 5/4, dry), dark yellowish brown (10YR 3/6, moist) with 20% gravel
AGL-BF-OP3	30	Reclaimed site: Oil palm farm intercropped with plantain and pineapple, 3 years old; Sandy texture, brown (7.5 YR 5/4, dry) and dark brown (7.5YR 3/4, moist), received soil adequate soil management than others
AGL-RLF-6	20	Reclaimed site afforested with *Leucaena leucocephala* (Lam.) de Wit, 6 years old; Sandy texture, light brownish grey (10 YR 6/2, dry) and dark greyish brown (10 YR 4/2, moist)
AGL-RMCF-6	20	Reclaimed site of mixed cocoyam, cassava and plantain farm, 6 years old; Sandy texture, light brownish grey (2.5 Y 6/2, dry) and greyish brown (2.4 Y 5/2, moist)
AGL-ABMT-2	30	Abandoned mine tailings invaded by *Portulaca sp.* L., *Cyperus sp.* L, *Chromolaena odorata* (L.) R.M. King & H. Rob., *Leucaena leucocephala*, and *Gliricidia sp.* (Jacq.) Kunth. Ex Walp., 2 years old; Silt, pale yellow (2.5 Y 7/4, dry), olive brown (2.5 Y 4/4, moist)
AGL-RMT-OP3	30	Reclaimed mine tailings: Oil palm farm with *Pueraria phaseoloides* (Roxb.) benth. as a cover crop, 3 years old; Light yellowish brown (2.5 Y 6/3, dry), olive brown (2.5 Y 4/3, moist)
AGL-WR-0	Random grabs from heaps	Waste rock: Rock fragments invaded by ferns, *Chromolaena odorata*, *Cyperus sp.*, *Vigna sp.*, *Centrosema pubescens* Benth., < 1 year, greenish grey (10 Y 6/1, dry), dark greenish grey (10 Y 4/1, moist)
Bogoso Gold Limited		
BGL-UN-F30	30	Unmined natural forest, trees of 50 m high, > 30 years old; Loam, yellowish brown (10 YR 5/4, dry), dark yellowish (10 YR 4/4, moist)
BGL-FBF-0	30	Freshly backfilled and graded site yet to be re-vegetated, < 1 year old; Sandy loam, pale brown (5 Y 7/4, dry), olive (5 Y 5/4, moist)
BGL-RAF-3	20	Planted *Acacia mangium* Wild. forest, 3 years old; Sandy loam, pale brown (10YR 8/4, dry) and dark yellowish brown (10YR 4/4, moist)

Statistical analysis

With the exception of the WR, the post-mining sites from each mine concession were considered as a treatment with the five replicates in completely randomised experimental design with one fact. The sites at each mine concession were used as independent factors. The data were checked for conformity to the analysis of variance (ANOVA) criteria be conducting One-way ANOVA using SPSS version 20 (IBM Corporation). Statistical significance was set at 5% probability and the different means between were separated by Tukey post-hoc test. The carbonate data (from the WR and MTs) were analysed using Kruskal-Wallis H and Mann-Whitney U non-parametric tests because they were not normally distributed.

RESULTS AND DISCUSSION

Mineralogy and heavy metal contents

The geochemistry of a mine site has profound implications on post-mining land management due to issues such as acid mine drainage and heavy metals distributions and concentration levels. Managing such environmental issues can be very challenging since this constitutes a substantial cost. The XRD patterns of the samples revealed the dominance of kaolinite, muscovite and quartz (Tables 2 and 3) from both concessions and are common minerals of the Birimian and Tarkwaian systems (Oberthür *et al.*, 1995; AGL, 2002). These are minerals resistant to further weathering and have low CEC (Juo and Franzluebbers, 2003), which affects the quality of the soil because of the inherent low activity. Aside muscovite and quartz, the WR also contained albite, fraipontite and calcite. The MTs also contained ankerite, bobierrite, clinoclase and greenalite, which were absent in the WR. This suggests two possibilities: (1) formation of new minerals from the chemical constituents of the tailings, and (2) contamination of the MTs during disposal. Additionally, the MTs had more primary minerals and phyllosilicates compared to the mine soils (Tables 2 and 3). The $CaCO_3$ content (Table 5) of the WR was almost 5-5.8 times higher ($P = 0.002$) than the MTs. The abandoned MTs (AGL-ABMT-2) had 20% more $CaCO_3$ than the reclaimed MTs (AGL-RMT-OP3) (Table 5). From the XRD patterns, the MTs had no calcite but the $CaCO_3$ was in the form of ankerite. This difference could be explained by exhaustion of part of the carbonate during ore leaching, dissolution or through a new mineral formation. Thus, the ankerite in the tailings may have formed during tailings disposal, particularly if the Mg/Ca ratios and carbonate contents were high (Michałowski and Asuero, 2012). Nonetheless, the composition of MTs and WR can best describe the geochemistry of AGL-DG as acid-buffering where the weathering of $CaCO_3$ consumes H^+ (Hitch *et al.*, 2010). However, the two MTs differed slightly, probably because of the effect of the existing vegetation. For instance, there was 20% reduction in the $CaCO_3$ content of the reclaimed MTs, which suggests the effect of a dissolution process that might have occurred earlier. With time, the primary minerals in the WR and MTs may weather to form other minerals.

The MTs had 4.6 and 5.2 mg kg^{-1} Pb, 0.65 and 0.80 mg kg^{-1} As and 0.00 and 0.01 mg kg^{-1} Cd (Table 4) in the reclaimed and abandoned tailings, respectively. This constitutes 11 to 75% more metals in abandoned MTs (AGL-ABMT-2) than reclaimed MTs (AGL-RMT-OP3). The values are within ranges found in uncontaminated soils (Förstner, 1995; Kabata-Pendias, 2011). The reduction in the heavy metal contents of the reclaimed MTs might have been due to uptake or phytoextraction by the oil palm (Oviasogiea *et al.*, 2011) and other plants. The As data contradict those of Antwi-Agyei *et al.*

(2009) and Boateng *et al.* (2012) which revealed higher metal contents in decommissioned MTs at an Obuasi mine in Ghana. Obuasi is a hot spot of As activity related to mine geology (Smedley and Kinniburgh, 2002; Morin and Calas, 2006), mostly occurring in association with Pb and acid-generating sulphur-rich minerals (Xavier, 2006). With a wider coverage of the heavy metal analysis, there is the possibility of encountering other heavy metals as suggested by the mineralogy, particularly given the presence of clinoclase and fraipontite (Tables 2 and 3). However, there are some that exist in smaller quantities, particularly at AGL-DGM. According to Oberthür *et al.* (1995), there are five primary gold mineralisation types in the Ashanti belt and AGL-DGM belongs to the Quartz-pebble conglomerates of the Tarkwaian Group comprising gold, magnetite and hematite while that of the BGL belongs to the sulphide ore group which is associated with quartz veins, with auriferous arsenopyrite as a major host of gold. This implies that the BGL may be loaded with substantial amounts of heavy metals, but due to limited access to sites, this could not be ascertained.

TABLE 2. Categories of crystalline minerals detected by XRD in the mine soils, mine tailings and waste rock showing their codes as used in Table 3 and their most characteristic d-values.

Mineral	Code	Chemical formula	d-values [Å]
Nesosilicates (3-D framework)			
Staurolite	STA	$H_2(Fe, Mg)_4Al_{18}SiO_{48}$	3.01, 2.69, 2.37
Phyllosilicates (sheet silicates)			
Muscovite	MUS	$KAl_2Si_3AlO_{10}(OH)_2$	10.0, 5.0, 3.48,
Kaolinite	KAO	$Al_2Si_2O_5(OH)_4$	7.10, 2.56, 1.66
Paragonite (mica)	PRG	$NaAl_2(AlSi_3O_{10})(OH)_2$	9.7, 4.82, 2.54
Fraipontite	FRP	$Zn_8Al_4(SiO_4)_5(OH)_8.7H_2O$	2.12, 1.99, 1.65
Greenalite	GRN	$(Fe, Fe)_{2-3} Si_2O_5(OH)_4$	7.12, 2.57, 1.59
Tectosilicates (3-D framework)			
Quartz	QTZ	SiO_2	4.26, 3.34, 1.82
Albite	ALB	$½(Na_2O.Al_2O_3.6SiO_2)$	3.21, 2.46, 2.24
Carbonates			
Ankerite	ANK	$Ca(Mg_{0.67}Fe_{0.33})(CO_3)_2$	2.89, 2.19, 1.79
Calcite	CAL	$CaCO_3$	2.49, 2.28, 2.09
Phosphates and Arsenate			
Clinoclase	CLN	$Cu_3AsO_4(OH)_3$	3.58, 3.35, 3.32
Bobierrite	BOB	$Mg_3(PO_4)_2.8H_2O$	2.94, 2.13, 1.58

TABLE 3. Crystalline minerals found in the mine soils, mine tailings and waste rock from the mining concessions represented by codes indicated in Table 2.

Management option	**Mineral codes showing their presence in samples from each post-mining management option**											
	QTZ	MUS	KAO	STA	ANK	FRP	ALB	CAL	GRN	CLN	BOB	PRG
Abosso Goldfields Limited- Damang Gold Mine												
AGL-UN-F30	X	X	X	X	O	O	O	O	O	O	O	O
AGL-BF-OP3	X	X	X	O	O	O	O	O	O	O	O	O
AGL-RMCF-6	X	X	O	O	O	O	O	O	O	O	O	O
AGL-RLF-6	X	X	O	O	O	O	O	O	O	O	O	O
AGL-ABMT-2	X	X	X	O	X	O	O	O	O	X	X	O
AGL-RMT-OP3	X	X	X	O	X	O	O	O	X	O	O	O
AGL-WR-0	X	X	O	O	O	X	X	X	O	O	O	O
Bogoso Gold Limited												
BGL-UN-30	X	O	X	O	O	O	O	O	O	O	O	O
BGL-FBF-0	X	X	X	O	O	O	O	O	O	O	O	O
BGL-RAF-3	X	O	X	O	O	O	O	O	O	O	O	X

X = Present; O = Absent

TABLE 4. Arsenic, cadmium and lead contents in the abandoned and reclaimed mine tailings of AGL-DGM.

Post-mining management	*As*	*Cd*	*Pb*
	mg kg^{-1}		
AGL-ABMT-2 (Abandoned)	0.80	0.01	5.17
AGL-RMT-OP3 (Reclaimed)	0.65	0.00	4.63

Soil pH and cation retention

The pH values of the samples grouped into acidic mine soils (pH 4.6-5.4) and alkaline MTs and WR (pH 8.5-9.3) compared to a pre-mine value of 4.2-4.6 (Table 5) for unmined soils. These corroborate those reported by Tetteh and Dedzoe (2004) in mine soils of Bogoso and by Boateng *et al.* (2012) in mine soils of Obuasi. Relatively high pH values have been found in mine soils in Rwanda (Neina *et al.*, 2017) and in eastern Ohio (Shrestha and Lal, 2011) compared to their unmined counterparts. This could be due to the homogenisation of top- and subsoils during stockpiling. Despite this, the pH values are within range for micronutrient and heavy metals toxicity that may be present to pose a challenge to plant growth. The alkaline pH of the MTs was due to carbonate-rich overburden which has acid-buffering potential (Hitch *et* *al.*, 2010) as indicated by the mineralogy (Tables 3 and 4). These values may eventually reduce through weathering and organic matter decomposition.

For soils of the humid tropics, cation retention (CEC and exchangeable base cations contents) is often a major problem because of pH-dependent charges (Juo and Franzluebbers, 2003). This is associated with kaolinite, muscovite and quartz, (Tables 3 and 4) which have low CEC (Juo and Franzluebbers, 2003). Further, it has been suggested that the intense weathering and leaching resulted in soils with low base saturation and pH (Sanchez *et al.*, 2003). The post-mining management did not significantly increase the cation retention of the sites except for AGL-BF-OP3 (Table 5). The CEC of AGL-BF-OP3, for instance, was 20% less than of AGL-UN-F30 (un-mined forest). This might be attributed to soil management practices such as mulching, cover cropping with *Pueraria phaseoloides*, erosion control and fertiliser application on the site. Consequently, the higher SOC and N_{total} contents were found and reflected on cation retention within 3 years of reclamation. This suggests that these mine soils require more intensive soil management practices that can sequester carbon and enhance soil quality.

Soil organic carbon and total nitrogen

The SOC and N_{total} of the sites clustered into relatively higher contents in the unmined forests, moderate contents in mine soils except for AGL-BF-OP3 and low contents in the MTs (Table 4). Interestingly, the SOC and N_{total} contents of the reclaimed oil palm farm (AGL-BF-OP3) were noticeable, almost approaching those of the unmined forests. As with the cation retention, these results are attributed to soil management practices and are consistent with the propositions of Harris *et al.* (1996), Anderson *et al.* (2008) and Liu *et al.* (2011) that proper reclamation procedures, re-vegetation with appropriate plants and soil nutrient amendments enhance the restoration of mine soil environments. Other studies have shown that reclamation can enhance soil quality (Shrestha and Lal, 2007), enhance productivity (Sperow, 2006), and accumulate more SOC than native forest sites (Stahl *et al.*, 2003; Sperow, 2006). These results were, however, obtained after 10 years of reclamation although a 15-cm thick A-horizon was formed within the first 5 years (Roberts *et al.*, 1988; Ussiri and Lal, 2005). On the contrary, the lowest SOC content was found in the MTs, which was only 7-11% of that in the other soils.

This is consistent with the results of Ye *et al.* (2002), Li (2006) and Boateng *et al.* (2012). The MTs are usually deficient in essential plant nutrients which affect plant growth (Williamson *et al.*, 1982; Norman and Raforth, 1998) because they are milled ore by-products. Thus, the only source of nitrogen in the MTs, in the short term, could be cyanide decomposition products plus limited biomass addition. Given the fine texture, mineralogy and low heavy metal contents, the MTs could be mixed with topsoils to improve mine soil quality during reclamation. The study indicated that the soil properties of the post-mining land management were mostly influenced by soil management. The study sites were less than 10 years old and only showed potentials of progressing towards rehabilitation.

TABLE 5. Mean (N = 5 ± one standard deviation) pH, $CaCO_3$, CEC, basic cations, SOC and N_{total} of the mine soils, tailings and waste rock from the post-mining management options at the mining concessions. Means in columns followed by different letters are significantly different ($P < 0.05$).

Management option	**pH_{water}**	**pH_{KCl}**	**$CaCO_3$**	**CEC**	**Basic cations**	**Organic C**	**Total N**
			$g\ kg^{-1}$	**$cmol_c\ kg^{-1}$ soil**		**$g\ kg^{-1}$soil**	
<u>Abosso Goldfields Limited</u>							
AGL-ABMT-2	8.5 (0.2)a	8.3 (0.1)a	5.8 (0.3)b	-	-	1.0 (0.0)c	0.1 (0.0)b
AGL-RMT-OP3	8.5 (0.2)a	8.1 (0.2)a	4.8 (0.6)c	-	-	1.0 (0.0)c	0.1 (0.1)b
AGL-BF-OP3	5.4 (0.1)b	4.5 (0.1)b	-	8.9 (0.3)a	4.0 (0.1)	16.0 (0.1)a	1.3 (0.3)a
AGL-RMCF-6	5.0 (0.1)b	4.2 (0.1)b	-	4.9 (1.0)b	3.0 (0.7)	9.0 (0.1)b	0.9 (0.2)a
AGL-RLF-6	5.1 (0.3)b	4.4 (0.3)b	-	4.1 (0.2)b	3.7 (0.8)	9.0 (0.1)b	1.0 (0.2)a
AGL-UN-F30	4.6 (0.1)c	3.9 (0.1)b	-	11.1 (0.9)a	4.3 (0.6)	18.0 (0.4)a	1.2 (0.3)a
AGL-WR-0	9.3 (0.2)	8.8 (0.1)a	27.8 (2.6)a	-	-	-	-
P value	*0.0001*	*0.0001*	*0.002*	*0.0001*	*0.640*	*0.0001*	*0.0001*
<u>Bogoso Gold Limited</u>							
BGL-RAF-3	5.2 (0.1)a	4.1 (0.0)	-	5.1 (0.4)b	1.0 (0.1)	4.0 (0.0)b	1.6 (0.3)a
BGL-FBF-0	4.6 (0.0)b	4.0 (0.0)	-	5.0 (0.5)b	1.3 (0.1)	6.0 (0.1)b	1.0 (0.1)b
BGL-UN-30	4.2 (0.1)c	3.5 (0.1)	-	13.7 (0.7)a	2.0 (0.3)	20.0 (0.2)a	1.9 (0.2)a
P value	*0.0001*	*0.001*	-	*0.0001*	*0.169*	*0.0001*	*0.0001*

Samples with high pH were not analysed for CEC and exchangeable base cations

CONCLUSIONS

The study showed that kaolinite, muscovite and quartz dominate the unmined soils, mine soils and mine tailings of both concessions. The presence of these minerals have implication on the quality of the mine soils and the rehabilitation process. Further, based on the results, the As, Cd and Pb contents of the MTs were in the range of those in uncontaminated soils, implying that heavy metal pollution is from a natural sources and not a challenge at those concessions. Additionally, the soil management practices adopted for the reclaimed site under oil palm enhanced the SOC, N_{total} and the cation retention of the mine soils in the short term. This suggests that all mine reclamation and rehabilitation efforts should make integrated soil management a priority over re-vegetation, particularly in reclamation for agriculture.

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