

Plant litter turnover, soil chemical and physical properties in a Ghanaian gold- mined soil revegetated with *Acacia species*

Frimpong, K. A.¹, Afrifa, E. K.A.², Ampofo E. A.¹, Kwakye P. K.¹

1- Department of Soil Science, University of Cape Coast, Ghana

2- Department of Environmental Science, University of Cape Coast, Ghana

e_afrika@yahoo.co.uk

doi: 10.6088/ijes.2014040404546

ABSTRACT

The effects of stand-age of *Acacia sp* on plant litter turnover and decomposition, soil physical properties and nutrient elements were studied in revegetated gold-mined soils. Litter in the 3- and 6-year plantation soils were significantly lower ($P < 0.05$) than the forest soil, whilst 9- and 12-year old revegetated soils had litter significantly higher ($P < 0.05$) than the forest soil. Biomass decomposition constants measured in all treatments were statistically similar, ranging from 1.03 in the forest soil to 0.94 in the revegetated treatments. Total N concentrations were higher in the forest, 12- year and 9- year revegetated treatments and varied from 0.20% to 0.50%. Organic carbon concentrations followed the increasing trend 3-year < 6- year < 9-year < 12- year < forest. Exchangeable K concentrations measured in all the soils were lower than 0.6 cmol kg⁻¹. Field moisture capacity (12.6 – 20.3 %) and infiltration rates (25.2 – 31.1 cm h⁻¹) in the 3-year, 6-year and 9-year stands were significantly lower than in the forest and 12-year stand whilst soil bulk density values were higher in the 3-year, 6-year and 9-year than in the forest and 12- year stands. The study indicates that after 12 years of revegetation with *Acacia sp*, soil physical characteristics such as bulk density, moisture holding capacity and infiltration rates improved to levels comparable to those found under un-mined soils and that revegetation is a good strategy for restoring the fertility of gold-mined soils.

Keywords: Plant litter turnover, decomposition constant, *Acacia sps.*, revegetation, mining.

1. Introduction

Anthropogenic environmental stresses including surface mining activities can disturb primary productivity, biodiversity and soil nutrient cycling patterns, resulting in land degradation. The exploitation of mineral resources often leads to extensive soil degradation through the destruction of vegetation and alteration of microbial communities, resulting in low soil fertility and productivity (Jackson et al., 1990), Physical disturbances of the top soil during stripping, stockpiling and reinstatement have adverse implications for soil fertility as these processes can cause negative changes in soil moisture holding and infiltration capacities, bulk density and substantial nitrogen (N), phosphorus (P) and potassium (K) losses. The Food and Agriculture Organisation estimated that between 1990 and 2005, gold mining activities in Ghana contributed significantly to land degradation and loss of cultivable land, resulting in a loss of 26 % of the forest cover and 15-20 % of arable land at the Tarkwa, Ayanfuri, Dunkwa, Esaase and Bogoso mining areas in Ghana (FAO 2006), Reclamation of mined soils is critical to restoring the ecological integrity and the agricultural productivity of the soils because any restoration process which improves soil physical properties and the availability of major nutritive soil elements particularly, N, P, and K enhances the fertility and productivity of the

soil. On a smaller scale, soil fertility of mined soils can be restored by the addition of crop residues and animal manures, which supply nitrogen and organic carbon sources to stimulate microbial activity and increase soil nutrient availability. In areas where large scale mining activities have seriously degraded the soil, re-vegetating the mined soils with plant species that are adaptable to the physically and biochemically altered soil conditions appears to be the most sustainable option for restoring soil productivity. According to Sheoran et al. (2010), the re-vegetation strategy is widely accepted for mined soils restoration as the revegetated soils become protected against the effects of accelerated erosion, which lowers soil nutrient concentrations through increased soil loss. Further, the rapid decomposition of plant litter due to enhanced microbial activity in revegetated soils promotes soil nutrient cycling and increases soil nutrient concentrations in accordance with the principles of sustainable soil ecology management. Many re-vegetation efforts have employed N-fixing, heavy metal – and acid-tolerant leguminous species, grasses, herbs, and trees for effective reclamation of acidic and heavy metal-bearing soils. Once the re-vegetation process has begun and plant species have been established, the reclaimed soils need to be frequently assessed to establish their capacity to support crop production in terms of major soil nutrient element availability. This study therefore examines how the age of the *Acacia* species affect litter turnover and decomposition, soil physical properties and nutrient element (organic C, inorganic N and available P and K) concentrations in a revegetated gold mined Ghanaian soil.

2. Material and methods

2.1 Experimental site

The study was conducted at Ayanfuri in the Central Region of Ghana (5° N 0° W), It lies within the semi-deciduous forest zone of Ghana with a mean annual rainfall of 1500mm exhibiting a double maxima pattern (Dickson and Benneh, 1988), Revegetation of the mined soils at the study area had been done in phases between 1993 and 2003 following surface mining activities by Anglogold Ashanti Ghana Limited. The site covers a total area of 400 m². The stockpiled native topsoil was back-filled before *Acacia* species (*Acacia auriculiformis*) were planted at an average density of 650 trees per hectare.

2.2 Experimental procedure

Grid sampling was done at each site covering an area of 10 m × 10 m (100 m²), The differently aged *Acacia* plantations: 3, 6, 9 and 12, respectively (in years) served as the blocks, with each study plot further subdivided into 4 sub-plots of 25 m² each to serve as replications. A primary forest bordering the area, which had developed on soil with the same parent material, was used as the control treatment.

2.2.1 Soils

The soils studied were moderately well-drained, gritty sandy loams and clays developed in situ over deeply weathered coarse-grained biotite granite found on summits and upper slopes. They belong to the Nta and Ofin associations and classified as Rhodic Ferralsols (FAO, 1988), The chemical and physical properties of the soils studied are summarized in Tables 2 and 3 respectively.

Composite soil samples were obtained from each of the 5 sites using the systematic soil sampling procedure described by Jacobson (2002), The soil samples were sieved through a 2 mm mesh and repacked into sampling bags for laboratory analysis. The fine earth (< 2 mm) fractions were used for analyses of selected physical and chemical properties whereas undisturbed samples (core samples) were used to determine soil bulk density and infiltration capacity.

2.2.2 Assessment of aboveground litter content

Within each of the subplots, 3 labeled, 1 m x 1 m x 0.3 m wooden litter traps were randomly placed 1 m above the ground. Litter collected in the traps were removed once a week and put into correspondingly labeled nylon bags. The litter collected were separated into leaves, twigs (wood pieces < 1 cm in diameter), flowers and fruits and recorded as monthly totals every 28 days. Each litter component was oven-dried separately at 60 °C to a constant weight. The net primary production was estimated by multiplying the sum of the dry weights of all the components of the litter fall by 3.3 (Bray and Gorham, 1994),

2.2.3 Assessment of decomposition rate of leaf litter

Fifty grams of leaves collected from the forest floor were air dried and put into nylon mesh bags of 0.2 m x 0.2 m dimensions (Mwiinga et al., 1994), In each of the revegetated subplots, 40 nylon mesh bags were buried at random to a depth of 10 cm. The nylon mesh bags were covered with leaf litter to simulate a fairly good forest floor condition for maximum influence of meso- and macro-fauna (Lisanework and Michelson, 1994), Each site was clearly marked for easy retrieval after covering with litter. For each site, the weights of litter in 4 bags containing 50 g litter each dried to a constant weight at 60 °C were measured and averaged to represent the mean initial dry weight. Four bags were retrieved from each location at the end of every month for 12 months.

Litter decay constant (k) was calculated using a single exponential decay function adopted from Singh and Gupta (1997) as follows:

$$\frac{W_1}{W_2} = e^{-kt} \text{-----(1)}$$

Where, k is the decomposition constant.

To calculate k, the fomula was transformed into the equation:

$$\ln \frac{W_t}{W_0} = -kt, \text{ such that } k = \frac{\ln \left(\frac{W_t}{W_0} \right)}{t}$$

Where,

W₀ = initial weight of litter

Wt = weight of litter remaining after time t.

2.3 Laboratory Investigations

The core method (Blake and Hartge, 1986) was used to determine bulk density. Field moisture capacity was measured using a method adopted from Kutilek and Nielson (1994) and the infiltration rate determined by the double ring infiltrometer method (Bouwer, 1986), Soil texture was determined using the method of Bouyoucos (1962), Soil pH was determined in distilled water using a Glass electrode- Calomel electrode (McLean, 1982) MV Pracitronic pH meter. Soil pH was measured at a soil: water ratio of 1: 2. Organic carbon was determined using the wet combustion method of Walkley and Black (1934), Total N was determined using the method of Bremner and Mulvaney (1982), Available phosphorus was determined using the method of Bray and Kurtz (1945), Exchangeable bases were extracted with 1.0 M NH₄OAc (pH 7.0) and K in the extract determined by flame photometry (Chapman and Pratt, 1961), Thomas' (1982)'s method was used for the determination of exchangeable acidity.

2.4 Statistical analysis

Data obtained from the laboratory analysis and field work were subjected to statistical analysis to determine the mean values and the standard error of the means. Differences between the means were determined by analysis of variance (ANOVA) using the MINITAB 16 statistical software. Correlation analyses were conducted to determine the relationships between age of vegetation, above ground litter content, soil organic carbon and total nitrogen concentrations.

3. Results

3.1 Above-ground litter biomass production and decomposition rate

The amount of above-ground litter measured in the 3- and 6-year Acacia plantation soils were significantly lower ($P < 0.05$) than in the forest, but those measured in the 9- and 12- year plantation soils were significantly higher ($P < 0.05$) than in the forest soil. Among the revegetated sites, the quantity of above ground litter followed the trend 12-year > 9-year > 6-year > 3-year. Above-ground litterfall was generally higher in the dry season than in the wet season.

The experiments indicated that biomass decomposition constant, biomass C and N concentrations were not affected significantly by season. Biomass decomposition constant measured in the study varied from 1.03 in the forest soil to 0.94 in the revegetated treatments (Table 1), Biomass decomposition rates measured in all the treatments in this study were statistically similar. Organic C concentrations found in the forest litter were similar to those measured in all the Acacia revegetated treatments. Total N concentrations were however higher in the forest, 12- year and 9- year revegetated treatments than in the 6-year and 3-year revegetated treatments.

Table1: Annual litter fall, biomass decomposition constant, organic C and total N concentrations of litter from forests and Acacia species from revegetated mined soils

Treatment	Annual litterfall (t ha ⁻¹)		Biomass decomposition constant	Organic C (%)	Total N (%)	C:N ratio
	Dry season	Wet season				
Forest	8.82 ±0.59	7.02 ± 0.61	1.03 ±0.5	48.5 ±6.2	1.9 ± 0.2	25.5 ± 2.3
3Y	4.26 ± 0.08	3.12 ± 0.26	0.94 ±0.7	42.1 ±6.3	1.75 ±0.55	24.02 ±0.6
6Y	8.12 ± 0.49	6.11 ± 0.207	0.99 ± 0.6	44.5±5.3	1.82 ±0.47	24.2 ± 0.9
9Y	9.79 ± 0.20	8.08 ± 0.41	0.97 ± 0.7	47.0±3.7	2.0 ±0.69	23.5 ±0.7
12Y	10.62 ± 0.15	9.11 ± 0.21	0.96 ± 0.6	47.6±6.4	2.18 ±0.8	21.8 ± 0.7

3.2 Soil chemical characteristics

Selected soil chemical properties measured in the forest and revegetated soils are presented in Table 2.

Table 2: Selected chemical properties of forest and revegetated mined soils

Treatment	Season	pH	O C %	Exch. acidity cmol kg ⁻¹	CEC cmol kg ⁻¹
Forest	Wet	5.1	1.15 ± 0.09	1.4 ± 0.01	25.1 ± 1.2
Forest	Dry	5.0	1.17 ±0.03	1.3 ± 0.05	28.3 ± 2.2
3Y	Wet	3.6	0.66 ± 0.13	3.1 ± 0.01	6.6 ± 2.4
3Y	Dry	3.6	0.72 ± 0.17	3.2 ± 0.01	8.2 ± 1.9
6Y	Wet	4.0	0.70 ± 0.10	2.3 ± 0.01	10.1 ± 1.3
6Y	Dry	4.1	0.79 ± 0.11	2.4 ± 0.01	12.1 ± 2.0
9Y	Wet	4.3	0.79 ± 0.20	1.30 ± 0.01	12.2 ± 3.3
9Y	Dry	4.2	0.82 ±	1.75 ± 0.12	11.5 ± 0.03

			0.19		
12Y	Wet	5.6	1.02 ± 0.19	1.79 ± 0.20	21.4 ± 0.02
12Y	Dry	5.5	1.07 ± 0.19	1.85 ± 0.13	19.5 ± 0.02

Soil pH was less than 6 in all the soils (Table 2), The soil pH measured in the 12 year revegetated site was not significantly different from that found in the forest soil, but soil pH of the 3-, 6- and 9-year revegetated soils were significantly lower ($P < 0.05$) than in the forest and 12-year soils.

Total N concentrations measured across the soils varied from 0.20 to 0.50 % (Fig 1), The forest soil recorded the highest ($P < 0.05$) total N concentration while the 3-year revegetated soils recorded the least ($P < 0.05$), Total N concentration in the 12-year revegetated soil was significantly higher ($P < 0.05$) than the other revegetated soil and those measured in the 6- and 9-year revegetated soils were significantly higher ($P < 0.05$) than in the 3-year revegetated soils.

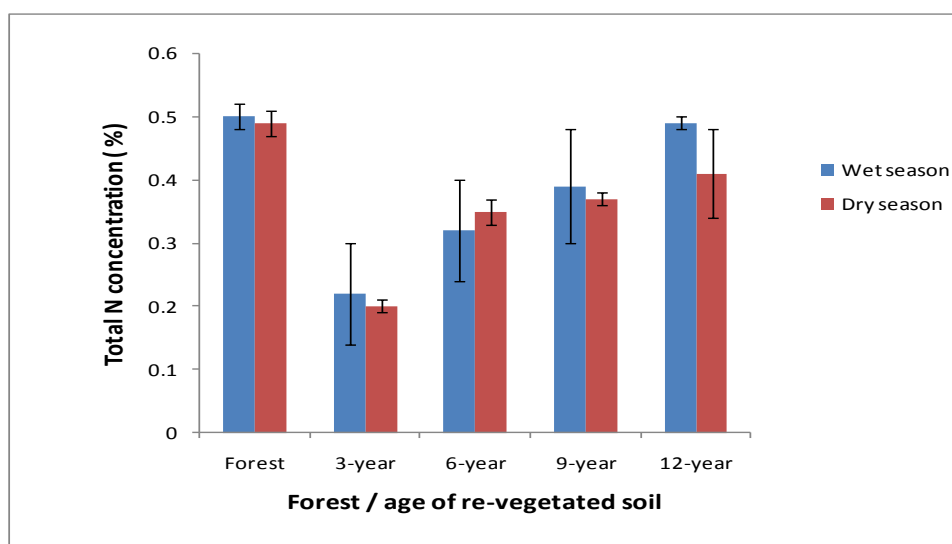


Figure 1: Percentage total N concentration in forest and revegetated mined soils

Total N concentrations ranged from 0.20 to 0.49 % in the dry season and were highest ($P < 0.05$) in the forest soils while the least ($P < 0.05$) were found in the 3-year revegetated soil. However, no significant difference was found between total N concentrations in the forest and 12-year revegetated soils.

During the wet season, NH_4^+ and NO_3^- concentrations measured in all the soils varied from 11.6 to 22.8 mg kg^{-1} soil and 6.2 to 14.1 mg kg^{-1} soil, respectively (Fig 2 a and b.), In the dry season NH_4^+ concentrations ranged from 27.4.2 to 11.7 mg kg^{-1} soil while NO_3^- concentrations varied from 6.6 to 16.0 mg kg^{-1} soil. NH_4^+ and NO_3^- concentrations were highest ($P < 0.05$) in the forest soil, but among the revegetated soils, NH_4^+ and NO_3^- generally increased with age of the vegetation from 3 years to 12 years after planting

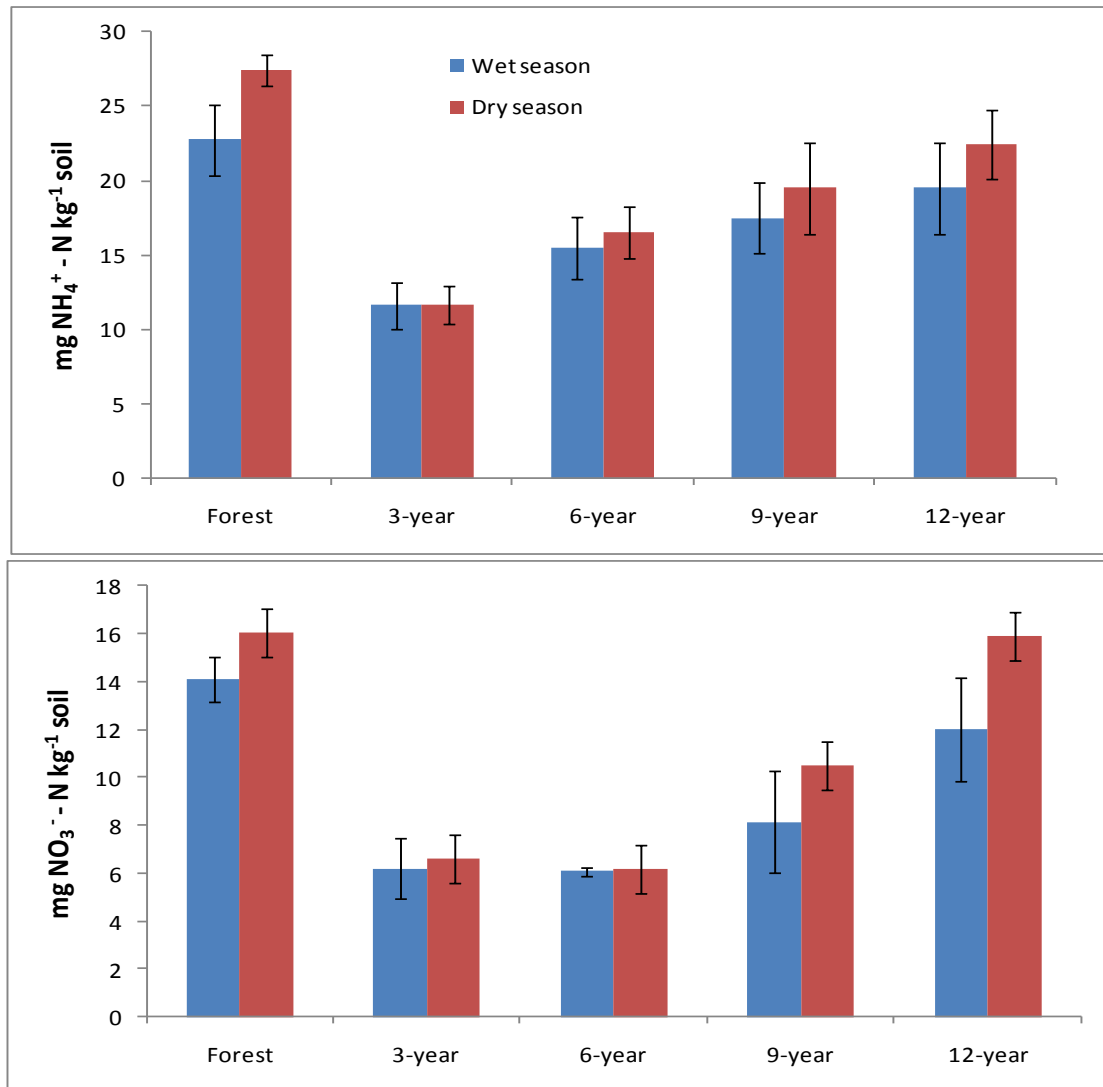


Figure 2: NH₄⁺ -N and NO₃⁻ - N concentrations (mg kg⁻¹) in forest and revegetated mined soils

Organic carbon concentrations measured in soils from the various sites varied from 0.66 to 1.17 %, respectively (Table 2), Soil organic carbon concentration in the forest soil was significantly higher ($P < 0.05$) than in all the *Acacia* plantation sites. Among the revegetated soils, organic carbon concentrations followed the increasing trend 3- year < 6- year < 9-year < 12- year revegetated soils, respectively. Furthermore, organic C concentration measured in the forest and in all the revegetated soils were significantly higher ($P < 0.05$) in the dry season than in the wet season.

The highest exchange acidity concentration (3.13 ± 0.01 , $P < 0.05$) was measured in the 3 year revegetated treatment, followed by the 6 year revegetated treatment (2.28 ± 0.02) (Table 2), The least ($P < 0.05$) cation exchange capacity (CEC) was measured in the 3 year revegetated soils. CEC in the 6 year, 9 year and 12 year revegetated soils were similar, but lower than that in the forest soil (Table 2),

Available P concentrations measured during the wet and dry seasons in the forest soils, 6-year, 9-year and 12-year soils were significantly higher ($P < 0.05$) than in the 3-year revegetated soils.

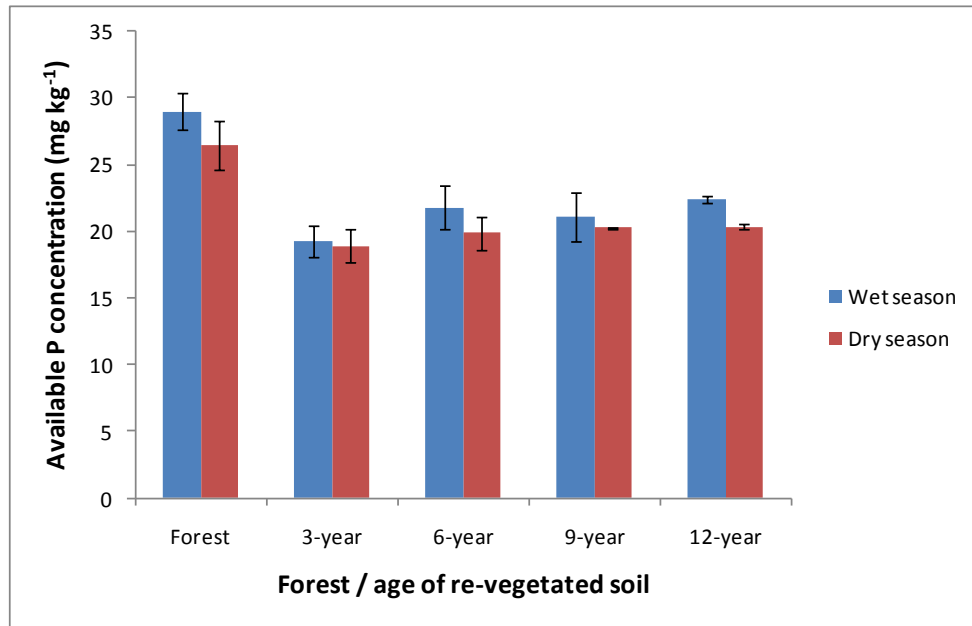


Figure 3: Available P concentration (mg kg⁻¹) in forest and revegetated mined soils

Exchangeable K concentrations measured in all the soils were lower than 0.6 cmol kg⁻¹ (Fig.4), However, concentrations measured in the 12-year revegetated soils were similar to those measured in the forest soils, and both were higher than in the other soils.

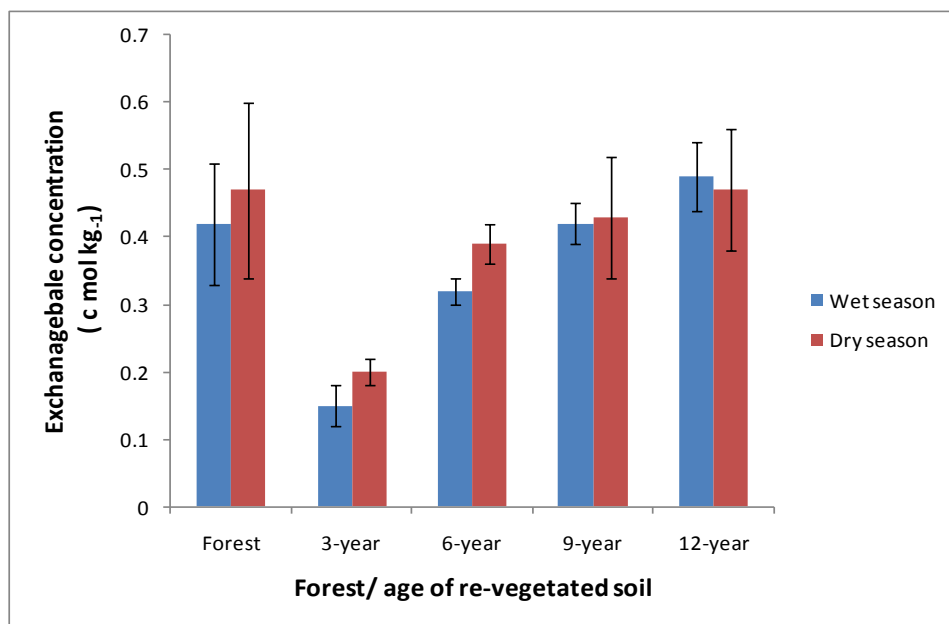


Figure 4: Exchangeable K concentration (cmol kg⁻¹ soil) in forest and revegetated mined soils

3.3 Soil physical characteristics

Soil bulk density, field moisture capacity and infiltration rates determined in the forest and revegetated soils are summarized in Table 3.

Table 3: Selected physical properties of forest and revegetated mined soils

Treatment	Sand (%)	Silt (%)	Clay (%)	Bulk density (Mgm ⁻³)	Field moisture capacity (%)	Infiltration rate (cmh ⁻¹)
Forest	60	20	20	1.41	23.1	30.4
3Y	65	20	15	1.78	12.6	25.2
6Y	64	22	14	1.72	14.8	27.8
9Y	64	21	15	1.60	20.3	29.9
12Y	62	22	16	1.56	22.3	31.1

Soil bulk density, field moisture capacity and infiltration rates in the 12 year *Acacia* treatment were all similar to values found in the forest soil. Field moisture capacity (12.6 – 20.3 %) and infiltration rates (25.2 – 31.1 cm h⁻¹) in the 3-year, 6-year and 9-year *Acacia* treatments were significantly lower than in the forest and 12-year *Acacia* treatments while soil bulk density values were higher in the 3-year, 6-year and 9-year *Acacia* treatments than in the forest and 12-year *Acacia* treatments, respectively.

4. Discussion

4.1 Aboveground litter fall

The study showed that aboveground litter fall increased with age of vegetation from 5.4 t ha⁻¹ at the 3-year revegetated site to 10.3 t ha⁻¹ at the 12 year revegetated site. This observation supports an earlier report by Atwill and Leper (1987) that the amount of litterfall correlates positively with tree size, which increases with age of the tree. Thus, older trees are expected to produce higher quantities of litter compared to younger ones because canopies of trees enlarge with age, resulting in increased production and dropping of litter. *Acacia* species have been reported to be among the most suitable species that have been used for rehabilitating mined soils (Jim, 2001) as they are fast-growing, able to produce high quantity and quality of litter and tolerate a range of soil types and soil pH values (Yamamoto et al., 2003). The quantity of aboveground litterfall measured in this study was up to 10 t ha⁻¹ yr⁻¹, which was in accordance with the report by Bernhardt et al. (1993) that *Acacia* species can produce between 7.5 to 9.0 t ha⁻¹ of aboveground biomass annually. In this study the highest amount of litterfall was measured in the 12 year revegetated treatment, but the amount of litterfall measured in the 9 year revegetated treatment (8.29 t ha⁻¹) compared favourably with findings by Garity and Mercado (1994) and Saugier et al. (2001) who reported that most *Acacia*

species reach their optimum litter production between 7 and 9 years. In contrast, Kessler and Breman (1996) found that Acacia species including *A. nilotica*, *A. senegal* and *A. tortiliis* recorded their highest litter falls after 12 years of establishment. They pointed out that differences exist in the growth patterns of various Acacia species and so their litter contributions are likely to vary and further suggested that the differences in litter production could also have been influenced by climatic and management conditions. According to Holtgrieve et al. (1999) the annual quantity of litterfall is dependent on the proportion of foliage biomass that dies within a year, which ultimately depends on such factors as rate of leaf senescence, wind velocity, variation in canopy architecture and the tree species that make up the forest (Jackson et al., 1990), In mature undisturbed forests the amount of litter that accumulates on the forest floor depends upon the equilibrium between liter fall and the rate of litter breakdown. According to Dutta (1999) litter fall acts as a critical regulating component to enrich the microbial biomass of mined soils. In this study, microbial biomass carbon positively correlated both with soil organic carbon ($r^2 = 0.84$, $P < 0.05$) and litter organic carbon content ($r^2 = 0.97$, $P < 0.01$), indicative that aboveground litter fall and subsequent release of organic carbon following decomposition significantly influenced microbial activity in the soil studied.

4.2 Decomposition of aboveground litter

In this study, the biomass decomposition constant measured in the forest soil was not significantly different from those from the revegetated sites. It however appeared that across the treatments, decomposition constants measured were higher in the wet season than in the dry season (Table 1), Wang et al. (1999) defined decomposition of leaf litter as weight loss due to a number of factors including the removal and/ or consumption of tissues by leaf-feeding invertebrates, leaching, and biochemical degradation by microorganisms and degradation during passage through the guts of invertebrates. Generally, warmer temperatures and higher precipitation result in higher rates of decomposition, leading to less organic matter accumulation. According to Vogt et al. (1995) these climatic factors interact with forest type, substrate quality and nutrient availability in soils, obscuring patterns within similar climatic and regional zones, but Zady et al. (1996) have noted that differences in decomposition rates during various seasons were mainly due to variations in temperature. In this respect Agehara and Warncke (2005) observed that litter decay under natural stands decrease by nearly 2% for each 1° C drop in temperature, but both Graves (2000) and Smith (2004) pointed out that precipitation was a more important factor governing litter decomposition than temperature. and that the highest decomposition of evergreen forest litter occurred in the late rainy season, concluding that litter disappearance in Nigeria was highest in the wet season due to activity of mites and collembola.

4.3 Effect of aboveground litter fall on soil organic carbon (SOC) and total nitrogen concentrations

Amounts of soil organic carbon vary considerably, ranging from 1 % or less in coarse-textured or highly eroded tropical soils to up to 3.5 % in prairie soils. However, SOC can be

up to 10% in poorly drained soils (Hassink, 1996), SOC in terrestrial ecosystems are determined by the difference between organic matter inputs and output (Gregorich et al., 1998),

The influence of seasonal variations on SOC storage involves the relationship between annual precipitation and temperature. Generally, wet and cool climates exhibit reduced decomposition and promote organic matter accumulation, while warmer climates favour accelerated decomposition of organic matter (Jenny et al., 1999), In contrast, Vanlauwe et al. (1997) found no effects of climate on average SOC within given soil orders. Organic C levels in mined soils are often low due to the disruption of ecosystem functioning, depletion of soil organic pool (Duttal and Agrawal, 2002) and loss of litter layer during mining activities. Spur et al. (2002) reported a strong relationship between litter decomposition and organic carbon in both the soil of forest ecosystems and forests.

In this study, above ground litter fall correlated positively ($R^2 = 0.51$ to 0.97 , $P < 0.05$) with organic carbon concentration in the soils across all the treatments (Table 4), According to Bray and Graham (2004) litter fall constitutes a pathway for both energy and nutrient transfer between plants and soils in forest land. Ovington (1994) also stated that much of the carbon and energy fixed by forests is usually added to the forest floor through litter fall, driving the C and N mineralization rates and influencing soil nutrient status. The aboveground litterfall measured in the study also correlated positively ($R^2 = 0.57$ to 0.66 , $P < 0.05$) with total N concentrations measured in soils from all the treatments.

Table 4: Pearson correlations between amount of litter fall, liter properties and/ or selected soil parameters and soil chemical properties

Relationships	Pearson Correlation co-efficient (r)	P value
Litterfall and Total soil N	0.75	0.001
Litterfall and ECEC	0.97	0.000
Litterfall and Available Soil P	0.93	0.000
Litterfall and SOC	0.91	0.000
Litter O C and SOC	0.86	0.000
Total litter N and Soil Total N	0.53	0.041
Litter OC and MBC	0.97	0.000
SOC and MBC	0.84	0.000
MBC and Total Soil N	0.90	0.000
Soil pH and ECEC	0.93	0.000
Soil pH and Exch. Acidity	-0.74	0.002

Litterfall positively correlated with total soil N ($r = 0.75$, $P < 0.001$), ECEC ($r = 0.97$, $P < 0.001$), available soil P ($r = 0.93$, $P < 0.001$) and SOC ($r = 0.91$, $P < 0.001$) Litter organic C positively correlated with MBC ($r = 0.84$, $P < 0.001$), C: N ratio was less than 30:1 in all treatments hence net N mineralization was expected.

4.4 Effect of revegetation on soil pH total N, inorganic N (NO_3^- and NH_4^+), available P and exchangeable concentrations

The pH of the 3-year, 6-year and 9-year revegetated were less than 6 can be described as strongly to very strongly acidic. This is reflective of the characteristic of a highly weathered soil. When the pH of soils drop below 5.5, legume and forage growth is reduced due to metal toxicities (such as aluminum or manganese toxicities), phosphorus fixation and reduced population of N-fixing bacteria. This inhibits plant root growth. Maiti and Ghose (2005) reported that pH vary from 4.9 to 5.3 in a mining dump site in India. In the 12-year and forest sites, pH values were 6.0 and 6.1 respectively, indicative of the ability for the revegetation strategy to improve soil pH. It must be emphasized however, that this effect is long term as pH values were similar to the forest values only after a 12 year period of revegetation.

Despite the impressive litter production by *Acacia* species, in this study the contribution to soil nitrogen was minimal to moderate, ranging from 0.35 to 0.41. Palm and Sanchez (1995) posit that the *Acacia* species may compensate for this situation by their nitrogen fixing ability. Previous authors including Coppin and Bradshaw (1982) and Sheoran et al. (2008) have shown that major nutrients such as N, P and K concentrations in mined soils are usually low, especially in the short term. In the long term, revegetation may result in increased soil organic matter content through litter deposition and decomposition. Organic matter is the major source of nitrogen, available P and K in unfertilized soils (Donahue et al., 1990), Ghosh et. al. (1983) have suggested that organic carbon greater than 0.75% indicates good fertility while Maiti and Ghose (2005) found that organic carbon is positively correlated with available N and K and negatively correlated with Fe, Mn, Cu, and Zn. The increase in organic carbon level is due to the accumulation of leaf litter and its decomposition to form humus.

Nutrient recycling and availability in reclaimed sites are reflected in part by the rate of decomposition of plant material. Although oxidation of soil nitrogen to nitrate may be impeded by acidic soils, C: N ratios of aboveground litter collected from each of the sites were lower than 30, indicative of the potential for net N mineralization. Available N (NH_4^+ and NO_3^-) concentrations in all the revegetated soils were lower than in the forest soil. In this study, bare mined soils were absent therefore, it would be difficult to ascertain whether N mineralization or net N immobilization occurred in the revegetated soils following decomposition of the aboveground litter. However, the NH_4^+ - and NO_3^- - N concentrations in all the revegetated soils were low suggesting that notwithstanding the high rate of litter turnover, mineral N availability was likely to be low.

Available P concentrations in all the soils studied were low, ranging from 9.3 – 19.0 mg kg^{-1} . The low available P concentrations may be attributable to the inherently low P levels in this

highly weathered tropical soil, which might have been exacerbated by low soil pH. However, the available P concentrations in the revegetated soils increased with increasing age of the vegetation in the same way as soil pH increased.

The management implications of these observations are that the type of fertilizer and application rates will vary, depending on the ages of revegetation activities. Cation exchange capacity (CEC) of the 3-year, 6-year and 9-year revegetated soils were lower than 24 cmol kg⁻¹ soil, which is not uncommon in highly weathered, low pH tropical soils. CEC of the 12-year revegetated and forest soils were 35 cmol kg⁻¹ soil. The relatively higher CEC in these soils is attributable to the high organic C contents in these soils. In the study, organic C concentration positively correlated with CEC ($r = 0.86$, $P < 0.001$) and negatively with exchange acidity ($r^2 = -0.74$, $P < 0.001$). The low pH in the 3-year, 6-year and 9-year revegetated soils could also have contributed to the low CEC in those soils as tropical soils are dominated largely by pH-dependent or variable charges, which influence their charge characteristics significantly (Frimpong et al., 2006), Maiti and Ghose (2005) concluded that it is important to increase the pH and organic matter content of soils for sustainable reclamation of mining overburdens.

4.5 Effect of re-vegetation on soil bulk density, infiltration rate and field moisture capacity

Changes in soil physical properties such as increased aggregation and bulk density, and reduced water infiltration and moisture-holding capacity associated with mined soil lower the potential of such soils for crop production. The bulk densities in the 3-year, 6-year and 9-year revegetated soils were up to 1.78 mgm⁻³, indicative that the soils may pose problems for root establishment. The relatively high bulk density values in these soils are consistent with the compact nature of mined soils due the presence of abundant rock fragments and concretions in such soils (Sheoran et al., 2010), Bulk density of productive natural soils generally ranges from 1.1 to 1.5 gcm⁻³. High bulk density limits rooting depth in mine soils. Plant roots are reported to grow well in soils with bulk densities of up to 1.4 g cm⁻³ and that root penetration is impeded significantly at bulk densities above 1.7 g cm⁻³. Soil compaction directly limits plant growth, as most species are unable to extend roots effectively through high bulk-density mine soils. The bulk densities in the forest and 12-year revegetated soils were lower than 1.55 gcm⁻³. This confirms that revegetation can improve soil stabilization soil through extensive root systems development, increased soil organic matter, lower bulk density and moderate soil pH, thereby improving soil nutrient availability. In revegetated soils, the plants accumulate soil nutrients and redeposit them on the soil surface in the form of organic matter, increasing soil nutrient availability following microbial breakdown (Li, 2006), According to Dorbgetor et al. (2012), topsoil depth, bulk density, porosity, aggregate stability, water content, soil strength, crushing and compaction of soils and water infiltration are all soil properties that can be altered by management practices.

Field moisture capacity of the revegetated soils varied from 10.2% in the 3-year revegetated site to 22.3 % in the 12-year revegetated site. The moisture holding capacity in the latter was

similar to that measured in the forest soil (23.1 %), Similarly, infiltration capacity also increased with increasing age of vegetation at the various sites from 10.2 cm h⁻¹ in the 3-year revegetated soil to 15.1 cm h⁻¹ in the 12-year revegetated soil. Infiltration rate in the forest soil was 15.4 cm h⁻¹. Increasing infiltration rates and moisture holding capacity could be as a result of decreasing bulk densities in the revegetated soils due to increasing organic matter from litter decomposition. Soil organic matter is responsible for binding soil particles (Gregorich et al., 1989) and improvement of soil porosity, which controls the amount of available water for vegetation (Davies and Younger, 1994), Soil microbial activity also declines when soil layers are compacted (Edgerton et al., 1995), but soils with active microbial communities are often well aggregated and vice versa. Soil microbes involved in organic matter decomposition produce polysaccharides that improve soil aggregation and plant growth (Williamson and Johnson, 1991),

Plant litter and root exudates provide nutrient-cycling to soil (Coates, 2005; Mertens et al., 2007) and leguminous trees potentially improve soil fertility through numerous processes, including maintenance or increase of soil organic matter, biological nitrogen fixation and uptake of nutrients from soil horizons below the reach of roots of under-storey herbaceous vegetation. They can also increase water infiltration and storage, reduce loss of nutrients by erosion and leaching, improve soil physical properties, reduce soil acidity and improve soil biological activity.

5. Conclusion

The study demonstrated that revegetation was a good strategy for restoring the fertility of gold-mined soils, but that the effect of revegetation on aboveground litter biomass, N, P and K concentration varied with the age of the revegetated soil. The study further showed that after 12 years of revegetation with *Acacia* species the soil physical characteristics such as bulk density, moisture holding capacity and infiltration rates improved to levels comparable to those found under un-mined soils. These observations were attributable to increased organic matter content in the revegetated soils, particularly in the 12-year revegetated soils, due to increased decomposition rate of aboveground litter.

It is however suggested that future research activities should examine how the revegetation strategy affects micronutrient dynamics in revegetated mined soils.

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