Options for Reclamation of Mine Tailings in West Africa

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OPTIONS FOR RECLAMATION OF MINE TAILINGS IN WEST AFRICA

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Abstract

Revegetation of tailings in West Africa presents two major problems when using established methodologies, in that soils have the potential to be highly alkaline, rather than acidic, plus the majority of recommended plant species are non-native to the area. Alteration of cap engineering however can modify hydrology, pH and morphology, allowing for a variety of habitats. Cover crops are often deep rooted, so may impact the capillary barrier, requiring possible modification in the depth of sub-soil and selection of species. Conversely, deep-rooted species are appropriate in avoiding erosion in sloped margins. Although some pioneer species, such as vetiver grass and *Prosopis* sp. are non-native, local species of this genera exist and should be trialled to establish both usefulness and invasiveness. Alkaline soils tend to suffer from nutrient deficiency. However, these can be suitable for savanna vegetation, with leguminous shallow-rooted shrub species providing available nitrogen. Succession to such a community can provide long-term stabilisation of biomass. Use of local species is preferable but local seed should be treated as a rare resource. Management regimes, such as burning, grazing and hand-pulling should be trialled and subsequent changes made, as required, to promote stability and biodiversity. This may also provide a suitable regime for growth of long-term crops and biofuels.

1. Mining in West Africa

West Africa has historically produced and delineated over 280 Moz of gold, with the region being cited as the fastest-growing gold-producing region in the world [1]. On a global scale, most of the prolific mines are on greenstone belts. These belts cover around 3,000,000 km^2 of West Africa, and the exploration potential of the region is substantial [1].

Diamond was the most significant mineral commodity to the economy of Sierra Leone, accounting for about 46% of export revenues in 2008 [2]. Other mineral commodities produced in the country included bauxite, cement, gold, ilmenite and rutile. In the past, the mineral industry had generated from 15% to 18% of the country's gross domestic product and 90% of its export earnings. It employed around 250,000 people before the forces of the Revolutionary United Front disrupted diamond mining operations in 1992 [2]. Mining activities have increased since the end of the civil war in 2002. However, industrialised mining has led to increased competition for land between mining companies and artisanal miners [3].

Guinea is amongst the world's leading producers of bauxite. Other mineral commodities produced in the country include cement, diamond, gold and salt. Undeveloped mineral resources include graphite, iron ore, limestone, manganese, nickel and uranium [3].

Liberia has continued to recover from a 14-year-long civil war that ended in 2003 and has made significant progress in the rehabilitation of the mining sector. Before 1990, this industry had contributed more than 65% of export earnings and represented about 25% of the country's gross domestic product [3]. In 2008, the only mineral commodities being produced in the country were cement, crushed stone, diamond, gold and sand. The mineral sector generated approximately \$6.43 million in revenues for the Government and employed an estimated 2,508 people [3].

Historically, mining has not played a significant role in the economy of Burkina Faso [2]. However, recent developments include the opening of a number of gold mines, with further and potential opening of manganese and zinc mines. Exploration for copper, gold, and uranium was ongoing throughout 2008 [2].

2. Tailings remediation

Tailings, the leach residue after mineral separation, often presents a threat to the environment as often these will contain such components as arsenic, sulphur and toxic metals. Use of a physical cover barrier (a cap) will reduce this damage where tailings are spread over land. Commonly, this cap may involve layering sand over the ground. Not only will those present a physical barrier but the sand will also act as a capillary layer between the tailings and an overlying cover layer. This capillary barrier increases the available water storage and adds protection against drainage into the tailings during storm events [4].

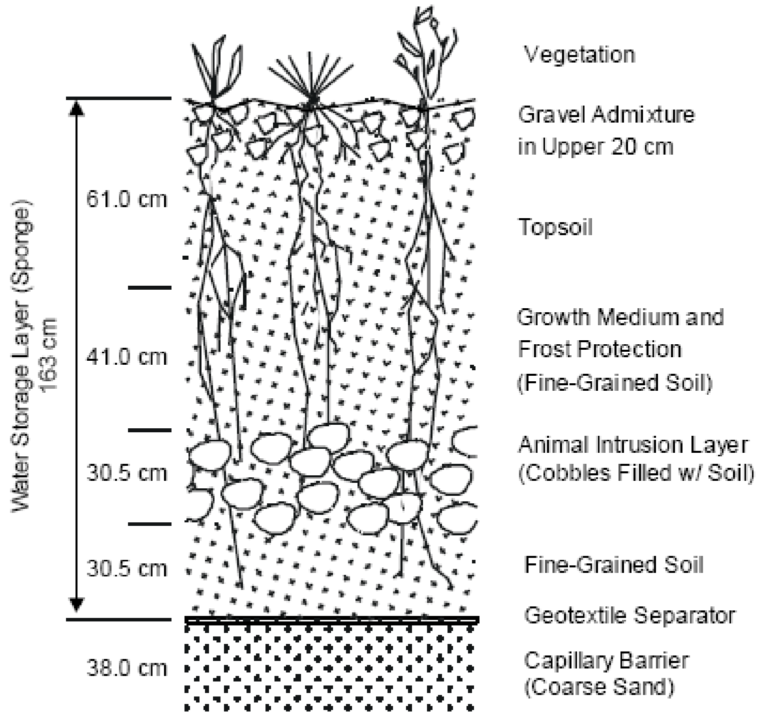

Figure 1: Example of a cover cap - taken from [5]

Use of nearby rock or overburden is commonly used as an additional, thicker barrier between tailings and the outside environment. Dry covers are generally effective in reducing infiltration into tailings materials. However, they do not completely eliminate infiltration. The efficiency of the store and release cover will be strongly affected by the presence/absence of vegetation [6]. Thus, a revegetation plan is essential, and may involve the use of regional grass/shrubs. Depending on the properties of the cover, an additional layer of organic material may also be required for vegetation growth.

Although revegetation strategies with named plants are available, many of these species are not native to West Africa. Indeed, it is doubtful a number of these species would even be capable of survival in such a climate. Instead, a botanist with West African expertise should peruse survey lists of in-situ species for plants that are closely related to recommended species.

3. Factors affecting vegetation

3.1 Root intrusion

Deep-rooted plants present potential problems when propagated over tailings. By extending into the tailings, the plants can translocate contaminants [4]. Also, by altering soil chemistry around the roots, vegetation may mobilise previously stable compounds. Macropores created by decomposing plant roots can also act as channels for water and gas, thereby bypassing soil barriers. Plants can also affect the hydrology of barrier systems through excessive extraction and clogging of drainage layers [4].

Root growth generally is limited to regions within the soil where extractable water is available. A capillary barrier has the effect of serving as an obstruction to downward flow [7]. Thus, the use of a capillary barrier can be developed to retain water close to the surface, thereby acting as a root intrusion obstacle [4]. Highly compacted soils cause stubby and gnarled root growth and can reduce rooting depths. However, at arid and semiarid sites, root densities can be higher in buried clay layers and cause seasonal desiccation [4].

3.2 Alkalinity

Use of savanna soils over tailings creates the potential for a strongly alkaline soil (>9 pH). It is rare to find plants able to tolerate extreme alkalinity. Thus, species with recorded instances of survival in such harsh environments should be utilised as pioneer vegetation. Further species that are either shallow-rooted (assuming alkalinity increases with depth) or/and capable of tolerating moderately alkaline soils (i.e. <9 pH, with preferably <8.5 pH) can also be propagated following soil amendments where necessary. Soil pH in the range of 7 to 8 is adequate for plants adapted to arid soils [8].

Alkaline soils tend to have a poor soil structure, leading to a low infiltration capacity. As rain water stagnates on top, irrigation becomes difficult and crops are limited to those that can withstand water-logging, such as rice [9]. After a soil is flooded, regardless of its original pH before flooding, the pH will approach neutrality [10].

3.3 Nutrient status

One of the commonest problems of degraded terrestrial environments is lack of nutrients, particularly nitrogen. Fertilisers may be utilised to increase soil nitrogen but this is both financially costly and labour intensive. Instead, introduction of nitrogen-fixing (leguminous) plants are recommended. By contrast, nutrients such as phosphorus must be provided and will remain deficient if not added [11]. As leguminous plants take time to establish, nitrogenous fertiliser should be applied several times, as required during the establishment period, to ensure maximum uptake [12].

4. Pioneer vegetation

The use of pioneer vegetation/cover crops will stabilise material and reduce surface winds, thus combatting erosion, whilst affording some shade [12]. By providing a less extreme micro-environment, soil conditions suitable for establishing indigenous self-sustaining species may be achieved [13].

Where pioneer species pose a threat to the proliferation or diversity of indigenous species, these species should be removed in such a way so as to stimulate indigenous species' establishment and diversity [13].

Both vetiver and *Prosopis* sp. (see below) are quick growing, deep rooted plants. This has the advantage of rapid soil stabilisation. However, vetiver especially, has particularly strong root systems that may penetrate the capillary layer. Advice must be taken on the suitability for these plants on the substrate intended. It may be that one or other of these plants are suitable for areas of strategic importance, rather than the whole site.

4.1 Vetiver grass

Vetiver grass (*Chrysopogon zizanioides*) is a perennial grass of the Poaceae family, native to India. Vetiver can grow on both acidic (pH=3) and alkaline (pH=11) soils. *C. zizanioides* is infertile, propagates vegetatively and is non-invasive [14]. It is tolerant of heavy metals and highly resistant to insect pests and diseases [15]. Vetiver is immune to flooding, grazing, fire and other hazards [16]. When planted on highly alkaline (>9 pH) soils, vetiver was found to have reduced the alkalinity by 2 units from the surface layer to 1 m depth.

Although non-native and non-invasive, *C. zizanioides* can only reproduce vegetatively, with resultant high labour cost. *C. nigritana*, however, produces viable seed and is native to southern and west Africa. Trials, if positive, on the effectiveness of this species may reduce costs long-term.

4.2 *Prosopis* sp.

Prosopis juliflora is an evergreen tree species native to Central America. This deep rooted plant is highly tolerant to water stress, soil salinity and alkalinity. The plant generally reproduces through seeds and can, in some instances, spread rapidly, replacing the native flora. In India, *P. juliflora* has attained the form of a noxious weed invading grasslands, agricultural lands, sanctuaries and other terrestrial habitats, causing tremendous loss of biodiversity. *P. africana* is the only tropical African *Prosopis* species. It is found frequently on fallow land, on sandy clayey soils over laterite, although it tolerates most soil types [17]. *Prosopis* spp. is a leguminous tree and so serves as a nitrogen provider to the soil [18]. Advice, with possible trials, should be taken on the suitability of this plant, with any implications for invasiveness.

4.3 Sloped margins

Slopes, based on exposure, should be mulched to provide shade for seedlings and to reduce evaporation of moisture from the soil during the critical period of seedling establishment [12]. The vegetative cover provided by grass seeding, hydro-seeding or hydro-mulching is often effective against sheet erosion and small rill erosion [19]. However, on newly-constructed slopes, the surface layer is often not well consolidated, so even well-vegetated slopes cannot prevent rill and gully erosion.

Vetiver grass has been used effectively in slope stabilisation. These roots are, per unit area, stronger and deeper than tree roots. Vetiver's extremely deep and massive finely structured root system can extend down to two to three meters in the first year. Roots can penetrate a compacted soil profile such as hardpan and blocky clay pan common in tropical soils, providing a good anchor for fill and topsoil [19].

When planted closely together, vetiver plants form dense hedges that reduce flow velocity, spread and divert runoff water, and create a very effective filter that controls erosion. Since new roots develop from nodes when buried by trapped sediment, vetiver continues to rise with the new ground level. The fertile sediment typically contains seeds of local plants, which facilitates their re-establishment [19].

6. Habitats

6.1 Aquatic systems

In aquatic systems the problem is usually excess of nutrients. Once inputs into flowing systems are halted, recovery is usually rapid. However, this does not occur so readily in lakes. For lakes of limited size, the removal of the nutrient-rich bottom muds may be possible [11]. In other situations a totally different approach, using natural ecological processes that involve the manipulation of phytoplankton can be more effective [11].

6.2 Grasslands

Grasses are the most commonly seeded plants in revegetation programs, producing large amounts of biomass and adapted to initiate regrowth rapidly after mowing or grazing. Grasses have fibrous root systems which hold soil in place, thereby controlling erosion [20].

Savanna grass species tend to be shallow rooted and tolerant of nutrient-poor, thin soils. Although unlikely to cope successfully with extreme pH, the shallow rooted nature means the grasses are able to avoid high pH and anoxia at depth. These plants, however, prefer well-drained substrata. Use of varied topography, sloping capillary barriers [7], soil depths and topsoil composition can create environments suitable for this assemblage, whilst also promoting wet grassland species in deeper, wetter tracts.

6.2.1 Forage species

Cramb., Purcell [21] state that many forage species can grow in alkaline soils, however *Brachiaria humidicola* is particularly recommended. Other species of fodder grass listed and native to Africa, include

Andropogon gayanus, Brachiaria brizantha, B. decumbens, B. ruzizensis, Pennisetum purpureum and *Setaria sphacelata*.

6.3 Trees and shrubs

A woodland plant community consisting of deep-rooted species is undesirable [4] due to the potential to infiltrate tailings. Thus, for in-situ habitats, re-establishing forest communities is unsuitable.

Aframomum stands, common in savanna environments, may be suitable as these shrubs have a short, scaly rhizome with a surface root system [22]. The species has a long history of use as a spice and a variety of medicines.

6.3.1 Leguminous trees and shrubs

The use of leguminous species increases the nitrogen component of the soil by the fixing of atmospheric nitrogen.

Acacia spp. have adaptable root systems capable of surviving in a variety of soil types. The compacted cover cap should encourage a shallow-rooted adaptation.

Leucaena leucocephala is a commonly used leguminous shrub in West Africa. Although well adapted to alkaline soils, this species can be extremely deep-rooted (>5 m), thus reducing the likelihood of usefulness. In shallow duplex soils, however, roots have been observed to branch and grow laterally at only 300 mm depth due to an impermeable clay layer [23].

Leucaena sp. is not tolerant of poorly drained soils, especially during seedling growth, and production can be substantially reduced during periods of waterlogging. However, once established it can survive short periods of excess moisture [23].

Gliricidia sepium, although native to South America is planted as an agroforestry tree in West Africa. It will tolerate only mildly alkaline soils, although trees established from cuttings will have a shallow root system and a short bole [24].

6.4 Wetlands

Waterlogged habitats, despite the initial pH of the soil, tend to return to neutral [10]. Naturally, this is dependant upon the incoming water, for instance, highly alkaline inputs would result in highly alkaline water but, for the most part, rain water would result in a pH of around 7. Along the littoral belt of West Africa, a number of alkaline lakes are present, with pH values approaching 8.5 in some cases - see [25] for example. So, it would appear that local vegetation could be sourced to support such a habitat. Other common wetland species, such as *Phragmites australis* and *Typha* spp. are also capable of survival in moderately alkaline environments.

The capillary layer to isolate tailings from soils depends upon retarding the infiltration of surface water. Measurements have suggested that vegetated capillary layers are extremely successful at impeding the downward drainage of water [26]. However, in waterlogged habitats, this may not be the case. Thus, although wetland vegetation may be suitable for alkaline environments, it is possible that additional engineering considerations may be required to prevent the interaction of tailings and soil.

6.5 Crops

By encouraging sustainable management of these crops, it is in the best interest of the farmers to ensure long-term rehabilitation of the soil. Naturally, suitability of crops for human/animal feed must be monitored. Use of crops for biofuels may also be considered.

It should be noted that the quality of irrigation water is important. Irrigating with water containing high bicarbonate content will often result in a saline soil. The use of gypsum can reclaim these soils.

Alternatively, the use of halophytes (possibly for food or fodder) can reduce salt in soils where the species hyper-accumulates within tissues. These species, such as *Atriplex* or *Salicornia* sp., tend to be tolerant of alkaline soils (although not severely alkaline) and extreme weather conditions, such as high sun and flooding events.

Grain crops such as *Sorghum* spp., wheat (*Triticum* spp.), barley (*Hordeum vulgare*), maize (*Zea mays*) and millet, along with sugar cane (*Saccharum* sp.), are tolerant of an alkaline soil, although these are rarely reported as growing above 8.5 pH. However, all these crops are reasonably deep-rooted, attaining depths of often over 1 m. Nevertheless, soil structure and moisture can have significant impacts upon rooting depth, thus advice from an agricultural expert is advised. Sorghum and millet are often grown for stabilising purposes due to their ability to grow in poor soils, combined with their strong, deep-rooted nature.

Other crops such as okra (*Abelmoschus esculentus*) and pepper (*Capsicum* spp.) are capable of surviving on moderately alkaline soil, however, roots can extend deep into the soil. Nevertheless, okra and pepper also develop significant shallow lateral roots, as well as a deeper taproot, so consultation with an agricultural expert is advised.

Cassava (*Manihot esculenta*) is an important crop in West Africa and grows well in soils of pH 8-9 (as well as more acidic conditions). Cassava is also tolerant of nutrient poor, metal rich soils, as found in slash-and-burn vegetation. This species is also shallow-rooted, being concentrated in the first 30 cm of soil [27].

Cowpea (*Vigna unguiculata*) and pigeon pea (*Cajanus cajan*) are leguminous plants used as food and fodder crops. These plants have well developed taproots which can grow to a depth of around 1 m or more, lateral root in the subsurface region bear numerous Rhizobium nodules [28]. These are occasionally used in erosion control as a cover crop. Like other legumes, these species fix atmospheric nitrogen and thus contribute to the available nitrogen level in the soil [28]; [29], similar to peanut (*Arachis hypogaea*). Peanut has been observed to compensate for the loss of the deeper taproot by the development of increased lateral roots [30]. Such adaptations could increase the fertility of the shallow soil.

The roots of rice (*Oryza sativa*) can vary dramatically dependant upon soil properties. However, 90% of the roots are contained within the top 200 mm of soil [31]. Alkaline soils tend to develop a hardpan, meaning water collects on the surface. Although harmful to many plants, this can actually be beneficial to species tolerant of waterlogging, such as rice. The waterlogging will usually ameliorate the alkali pH conditions of the soil – assuming the water itself is not highly alkaline [10]. Problems, however, may be encountered with phosphorus uptake.

7. Management Requirements

Traditional burning is the most common regime for maintaining savanna grassland, preventing succession to thicket and woodland [32]. This practice results in a habitat mosaic with increased biodiversity and woodland structure [33]. The introduction of leguminous species has reduced the need for this method of control. However, this can have the effect of promoting the woody component of savannas. Likewise, grazing has been seen to increase the woody component [34] and unpalatable species component [35]. By introducing separate compartments of fire-dependant savanna and grazing lands with pulling of woody species, a wider range of habitats is possible.

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