

Restoration of Forested Lands under Bauxite Mining with Emphasis on Guyana during the First Two Decades of the XXI Century: A Review

Susy Lewis, Judith Rosales

University of Guyana, Faculty of Agriculture and Forestry, Georgetown, Guyana

Email: susy.lewis@uog.edu.gy, judith.rosales@uog.edu.gy

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Abstract

Mining poses a major environmental threat to tropical forest ecosystems, given its role in long-term forest degradation. Like Suriname, Guyana presents one of the less disturbed forested lands in South America. The local economy is improving, thanks to the development of mining which is primarily focused on gold, diamond, and bauxite. This, however, has resulted in long-term degradation of important forest ecosystems and the pollution of water bodies, and these have given rise to increasing concentrations of sediments. Taking into consideration the afore-mentioned, this review synthesizes, for the first time, literature which describes knowledge-based restoration practices in forested fragmented landscapes at different bauxite mining areas. The principal objective of this endeavor is to learn from case studies that have been carried out in the Neotropics especially in South America, with a view to applying best practices to the Guyana context. It has been found that mining presents a serious challenge for physical, chemical, and biological restoration. Comprehensive knowledge of the ecology of the landscape—structure and configuration, soil type, physical, chemical and biological properties, dispersal mode, and the identification and quantification/inventory of plant communities is critically important pinpointed for planning restoration programmes. The process of recovering some of the ecological functions of the pristine forest, through natural regeneration, is vital to supporting biodiversity in overburden dumps and to mitigating environmental impacts. One of these many functions, functional connectivity, can be enhanced to optimize the restoration of forest cover leading to an increase in local biodiversity. Bearing in mind the afore-stated, this review synthesizes passive and active restoration through reforestation with local and exotic species, ecological management of colonization, nucleation practices, and the use of Landscape Ecology models. These have been identified as the most appropriate to follow,

given that a spatially driven design can provide much needed knowledge of the restoration/reclamation plan for Bauxite Mine Lands. Ecologically sound designs are a catalyst for devising mechanisms which can (help to) reduce environmental impacts. These designs can also help to boost the velocity at which ecological processes operate, in order to increase the resilience of ecosystems and the connectivity between forest patches and continuous pristine forests.

Keywords

Bauxite Mining, Connectivity, Forest Degradation, Guyana, Reclamation, Restoration

1. Introduction

Tropical forests are very important in the Neotropics, especially in the Amazonia of South America (which includes the Guiana Shield Region where Guyana is located). They contribute significantly to the carbon stocks and provide numerous goods and services (Meyer et al., 2019). In 1990, it was estimated that there were 1635 million ha of tropical forest and 964 million ha of other wooded lands; by 2010, however, the forest had decreased to 1514 million ha (Achard et al., 2014). Global Forest Watch has reported that tropical forests have been disappearing at alarming rates, in the last two decades, as a result of many pressures at different scales and levels. Only in the Amazon Forest has tree cover loss reached 2.4 million ha in 2019 (Global Forest Watch, 2014). Conrado da Cruz et al. (2020) reviewed forest loss and forest restoration over a 50-year period in Brazil, analyzing data from the Satellite Project of Brazil. Figures from the data show that forest restoration went from 27.699 ha in 1975 to 788.353 ha in 2018. The authors revealed that large efforts in restoration projects have been developed across the country.

Similar to the conversion of lands for agriculture and livestock (evident in Central America and Brazil, for example), mining is another main driver of deforestation, landscape fragmentation, soil and water quality degradation, and habitat loss (Busch & Ferretti-Gallon, 2017). Gold mining has been documented as the main driver of deforestation in South America; however, little attention has been paid to the impact of deforestation associated with bauxite mining (Lad & Samant, 2015). Even though the rate of deforestation associated with bauxite mining is small, the effect of land degradation is extensive and spatially important at local levels, especially if exploitation is done without any proper and sound plan for mining. A proper and sound plan for mining can significantly reduce the negative environmental impacts on terrestrial and aquatic ecosystems.

Bauxite mines are scattered in different ecological areas located in the borders of the Precambrian Cratons, both in Africa (Guinea, first in bauxite reserves in

the world) and South America. Guinea in East Africa contributes to 26.9% of the total reserve of the ore, while in South America and the Caribbean bauxite resources are estimated to contribute 21%, a range of 55 to 75 billion tons of bauxite ore (United States Geological Survey (USGS), 2020). Mineral production is a primary contributor to the Gross Domestic Product in these countries.

The Guyana REDD+ Monitoring Reporting & Verification System Year 6 Summary Report from January 1, 2015 to December 31, 2016 showed a decline in the area deforested from 2009 to 2016 (0.050% of the 18,452.16 ha of forested area) (The Guyana Forestry Commission & Indufor Asia Pacific, 2017). Nevertheless, there is difficulty in finding published information about quantitative annual deforestation data, specifically for bauxite mining in Guyana (Overman et al., 2019). It is a very small percentage of all deforestation.

In Brazil, the largest country in South America, bauxite mines are located in the watershed of the Trombetas and Guama Rivers, both tributaries of the lower Amazon River within the Amazon Forest lands. The Minas Gerais is located in the semi-deciduous forests outside of the Amazon watershed. Both of them are located in the borders of the Brazil Precambrian Craton. Additionally, the Bakhuis Bauxite Concession in Suriname is situated within the Bakhuis Mountains of Western Suriname (Corentyne River watershed) which is covered with a primary lowland humid forest (Lim, 2009). Los Pijiguaos in Venezuela is located in the watershed of the Cuchivero River, a tributary of the Orinoco River. In Guyana, bauxite mining has a very long history. It began in 1917 at Three Friends Mine, located to the south of McKenzie (now Linden), and later spread to Ituni and Kwakwani. The current mining operations are located on the East Bank of the Demerara River, south of Linden, and on the East Bank of the Berbice River. During heavy rainfall, unvegetated overburden dumps are prone to erosion causing sedimentation of adjacent rivers, as in the case of the Coomacka and Kara Kara Rivers in Linden (Figure 1) (Region 10 in Guyana).



Figure 1. Gullies erosion and sedimentation, dumps and wastelands of Bauxite Mining. Sites in Linden and Coomacka River in Guyana (Photographs from Susy Lewis).

Mineral extractions, such as gold and bauxite, are the major contributors to deforestation of the Amazon, and their operations are associated with serious environmental hazards. For example, the Trombetas bauxite mining operations are the underlying causes of the Amazonian deforestation (Sonter et al., 2017), even though the mine is located outside of the forest. These mining operations still have negative social, economic, and environmental impacts. These negative impacts include the collapse of the tailings dams of Fundão Dam in 2015, located in Mariana Town, Minas Gerais State, and the Brumadinho Dam in 2019, located in Brumadinho Town, Minas Gerais State (Kossoff et al., 2014; Palu & Julien, 2019). Traditionally, tailings used to be discharged into lakes (for approximately 10 years) which are located in the District of Porto Trombetas. When the discharge ended, after that period, about 30% of the area of the Igapo Lake and its flood prone vegetation was buried by bauxite tailings (Dias et al., 2014).

Forested landscapes are converted into fragmented landscapes, decreasing forests diversity and connectivity among habitats, hence the importance of doing a systematic review about bauxite mining as the underlying cause of this fragmentation. Besides, succession leads to restoration, and this process does increase forest diversity and connectivity among these forest habitats. In light of the afore-mentioned, the aim of this paper is to present a review of environmental degradation of forested lands under bauxite mining, focusing on recent ecological restoration tools and approaches which have been used in the last five years. Special emphasis is given to Guyana in the context of what has been developed for the Neotropics and South America.

The Conceptual Framework (Figure 2) summarizes the concepts and processes that are discussed in this review, considering that they can help to explain and direct the restoration process of forests in bauxite mining lands. The research literature has drawn attention to connectivity as the most important spatial function to restore in order to achieve the objectives of restoration. These

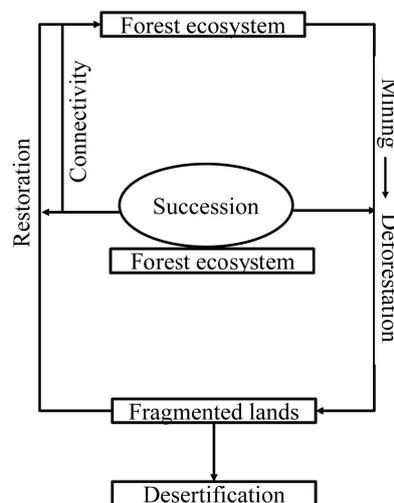


Figure 2. Conceptual framework (from Susy Lewis).

aims, which are some of the key ecological processes highlighted in this review, include species colonization, plant dispersion, and root infection of colonizers with arbuscular mycorrhizae.

Landscape Ecology Theory, with its spatial tools and approaches, is the most suitable to follow, considering that a spatially driven design can inform the restoration/reclamation plan for Bauxite Mine Lands (which to date has not been carried out in bauxite mines in South America). Ecologically sound designs aid in the development of mechanisms which can (help to) minimize impacts on the environment. These designs can also optimize the speed at which ecological processes operate (such as colonization) with a view to bolstering the resilience of ecosystems and the connectivity between forest patches and continuous pristine forests. In this regard, silvicultural techniques using plantations of native and non-native species—can be successfully incorporated when planning for closures of mines.

The conceptual framework shows the effect of mining as the main driver of deforestation, forest fragmentation and habitat loss and succession as the main process leading to colonization of a new physical environment by a series of vegetation communities increasing the connectivity within isolated patches.

2. Method

The review was carried out via a search in Google Scholar to access globally relevant journal articles. “State of the art” papers focused on those journal articles published between 2000 and 2020, articles which contained thematic keywords such as forests, mining, deforestation, ecosystems, restoration, succession, and connectivity. The objective of this specific search was to accrue relevant literature and to gain knowledge, from specific studies conducted, of the best approaches that have been reported globally during the last 20 years which have led to the effective restoration of forested lands in mining areas. The review was further downscaled Neotropics - South America - Guyana, with a restriction to bauxite mining. The search yielded various results: 1) 526 articles surfaced, using all thematic keywords; 2) 79 articles from them appeared for “Neotropics”; 3) 75 articles emerged, for ‘South America’, and 4) 18 articles popped up for “Guyana”.

Furthermore, Open Source databases such as ResearchGate and Sci-Hub, as well as proprietary source databases like Hinary and EBSCOhost, were used to access the important articles. The majority of the articles were open access and available through ResearchGate; if, per chance, these were not easily accessible, the article DOI was then introduced into the Sci-Hub database to acquire the articles sought. Moreover, the main purpose for the selection of these specific articles was to provide a systematic analysis for the understanding of key processes, the consideration of environmental variables, and the usefulness of ecological approaches in designing restoration plans for bauxite mining areas in Guyana.

3. The Importance of Restoration for the Mitigation of Forest Loss

Restoration of forest ecosystems which have been degraded is an important initiative that has been (and is being) promoted at the global, regional, and local scales. Initiatives like the Bonn Challenge, the New York Declaration of Forest, the 20 × 20 Initiative, and the AFR100 have resulted in the achievement of forest restoration (Crouzeilles et al., 2017). These undertakings include the planting of trees (for example, exotic trees), as well as the use of pioneer plant species as a facilitator for the establishment of shade tolerant species (Vicente-Silva et al., 2016). The process that drives this recovery of the forest ecosystem is succession—an ecological process which leads to species colonization of fragmented forests—which increases forests diversity and habitat connectivity (Sheffer et al., 2014).

Holl et al. (2017) reviewed different guidelines for the restoration of tropical forests. This author made specific reference to trends like the management of natural colonization, nucleation, and successional models, among others, which are catalysts for aiding the restoration process. On the other hand, Santini & Fey (2013) presented and demonstrated different ways in which a woody stage of succession can occur more rapidly on nutrient-poor substrate with minimal amelioration. These authors went on to say that succession can also take place at sites which are left untreated, in that natural vegetation of pioneer species may occur spontaneously. These successional studies assist restoration efforts of infertile soil or even when toxic substrates are present (Walker & Del Moral, 2009). Different models outlined in the Theory of Succession (or Succession Theory) help to explore ecosystem response to disturbances, and these models provide the framework for restoration research (Choi et al., 2008; Pulsford et al., 2016).

The choice of restoration approach depends on ecosystem resilience, restoration objectives or goals, landscape context, and projected costs (Holl & Aide 2011; Festin et al., 2019). Restoration processes of mine lands include physical, chemical, and biological processes. Physical methods focus on reconstructing landforms by means of ploughing, grading, smoothing and placement, and/or adding of topsoil (Shu et al., 2005; Sheoran et al., 2010; Festin et al., 2019). Restoration technologies have been used to improve soil organic matter such as composting, green manures, and the establishment of vegetation covers (Farrell et al., 2010). These technologies include Geo-nets, Bio-mats, Geo-cells, and Deep Rooting Plants (which have been introduced recently) (Rocco et al., 2016). Even though these technologies exist, there is still very limited knowledge about the restoration of mining lands (Barros et al., 2013).

Additionally, restoration refers to revegetation using propagules of different species produced, using either sexual or vegetative techniques. Colonization can be viewed as the net result of this process, starting from propagule production and ending in the survival to reproductive maturity of the colonist (Chazdon & Uriarte, 2016). The factors which control plant recruitment can be determined based on propagule pressure, i.e. the rate of propagule arrival (Reid & Holl,

2013). The study of the factors which control colonization accounts, firstly, for possible sources of propagule pressure (Tischew et al., 2014), and, secondly, for heterogeneous patterns of colonization (Sheffer et al., 2014). One such heterogeneous pattern, for instance, is dispersal which is the movement of individual propagules from their source site to another location where they can establish themselves and reproduce (Nathan et al., 2008).

The spatial pattern (configuration and composition) of patches and corridors within the landscape and disturbance are the main barriers to dispersal (Elliot et al., 2014). Based on empirical studies, these barriers are difficult to unravel due to limited replication at the landscape scale (Caughlin et al., 2016). Moreover, the measurement of distance in seed dispersal studies has complicated the issue of dispersal (Tamme et al., 2014). Many methods have been used over the years to measure dispersal distance of propagules such as seed traps, direct observations, and genetic markers. Models have also been designed to estimate this distance such as Mechanistic Models (Tamme et al., 2014), Time to Tree Canopy Closure Models (Caughlin et al., 2016), and Individual Based Behaviour Models (Levey et al., 2005). Consequently, restoration needs to be carried out, at the earliest opportunity, in order to prevent a significant loss of biodiversity (Gurr et al., 2014); in fact, restoration should be considered as the main strategy in recovering forest ecosystem that has been degraded (Romijn et al., 2019).

4. Landscape Ecology Theory in Ecological Restoration

Since the biological basis for restoration incorporates the spatial configuration of patches, corridors, and connectivity, this truth drives the researchers to the domain of the Landscape Ecology Theory which is (to be) applied in the restoration process. Almost every detail of ecological interactions creates a reciprocal relationship between ecological theories and restoration processes, and these provide opportunities for research (Falk et al., 2006). In this regard, the express aim of landscape ecology is to study landscape patterns and ecological processes at different levels and scales (Wu, 2013). Xie et al. (2020), in an extensive review of land degradation, indicated that in order to achieve a successful reconstruction of lands, research and models grounded in Landscape Ecology Theory are critical and must be considered. Therefore, a definition of landscape is the first prerequisite for landscape level research. It is also considered necessary for quantifying landscape patterns or studies of connectivity as functional metrics of resistance which can be applied to the restoration process (Newman et al., 2019). As such, a good understanding of landscape structure and its functions provides the necessary information for promoting biodiversity conservation (Gómez-Virués et al., 2015), planning, projecting, and evaluating restoration initiatives (Caughlin et al., 2019).

The most important characteristic of landscape ecology is the pattern-process relationship which strongly focuses on wide-scale ecological and environmental matters. In a nut shell, landscape ecology deals fundamentally with the interactions between biota and landforms (Turner, 2005). The development and dy-

namics of spatial heterogeneity, temporal interactions and exchanges across heterogeneous landscapes, and the scale-pattern observation process influence the management of biotic and abiotic processes (Crews-Meyer, 2006; Newman et al., 2019). Undisturbed tropical forests exhibit high levels of habitat heterogeneity (Holl et al., 2013). The process of fragmentation establishes the concept related to landscape heterogeneity (Mullu, 2016).

Environmental heterogeneity has a significant influence on the dynamics and structure of ecological communities, particularly topographic heterogeneity (which creates a complex mosaic of substrate varying in structure), hydrology, and chemistry. This mosaic differs in size, shape, content, and history, and these are all regulated by the scale factor and the development of hierarchies (Wu, 2013). For instance, the restoration of forest landscapes after severe mining disturbances presents significant challenges in the re-building of landform complexity and in the redevelopment of soil types (Macdonald et al., 2015). When studying landscape fragmentation, two types of spatial ecological theories are to be considered: the Island Biogeography Theory and the Theory of Metapopulation Dynamics. These theories establish that habitat configuration is important, above and beyond the effects of a loss in habitat area associated with fragmentation processes (Mullu, 2016).

5. Deforestation and Environmental Degradation in the Neotropics, South America and Guyana

The rate of tropical deforestation is unquestionably high in the Neotropics, particularly in Central America. In these parts, a greater percentage of forests have been cleared for agricultural purposes, particularly for food production (Busch & Ferretti-Gallon, 2017). This practice has led to extensive deforestation which has caused excessive erosion and soil degradation (Carr et al., 2006; Busch & Ferretti-Gallon, 2017). Forest clearing for large-scale food production has caused the displacement of thousands of rural farmers to urban areas due to little, limited, or no access to lands.

Several environmental impacts are directly associated with bauxite mining:

1) Deforestation: The rate of deforestation due to bauxite mining causes forest fragmentation. This has been proven to have detrimental and long-lasting effects for all species of plants and animals, the end result of which is a negative influence on the ecological services of the ecosystems for humans (Uemaa et al., 2013).

2) Forest Fragmentation: It is one of the primary consequences of land cover change, and it decreases habitat connectivity which alters biodiversity at the global, regional, and local scales (Crist, 2009; Uddin et al., 2015). It disrupts the dispersal mechanism (Jesus et al., 2012) (hence the extent and condition of native vegetation and biodiversity which have rapidly declined in recent decades), such that most species now live in fragmented patches of degraded habitat (Fletcher et al., 2018).

3) Landform and Soil Alterations: Bauxite mining directly modifies the topo-

graphy and stability of waste dumps due to increases in elevation and slopes. Topsoil is removed and soil profiles are severely disturbed, all of which result in the elimination of soil seed banks and rootstocks. Soil compaction occurs with increases in bulk density, alkalinity, salinity, and pH level. This has a slow and uncertain consequence on the natural recovery process of vegetation which also influences the soil microbial community structure (Sheoran et al., 2010).

4) Loss of Connectivity: Ecological studies have shown that dispersal by native species from one patch to another may be difficult, or sometimes impossible, due to the loss of connectivity among these patches. This loss of connectivity results in the inability of species to survive in fragmented landscapes, and these species are likely to disappear (Millenium Ecosystem Assessment, 2005; Reid & Holl, 2013; Villard & Metzger, 2014). Typical examples are the risk of extinction of a proportion of Amazonian tree species in the Amazon Forest (ter Steege et al., 2015). Another such risk is the ecological vulnerability of sensitive birds such as the Plain Pigeon (*Patagioenas inornata ssp. exigua*), the Crested Quail Dove (*Geotrygon versicolor*), and the Jamaican Blackbird (*Nesopsar nigerrimus*). These birds can all be found in the Cockpit Forest Reserve in Jamaica which is (being) threatened by bauxite mining, logging, and agriculture activities (Davis, 2017).

Consequently, it is important to understand the underlying causes and the time when habitat fragmentation effects occur, the environmental abiotic and biotic changes which develop, and their interaction with other human-induced changes (Fletcher et al., 2018).

Deforestation has physically changed forest landscapes in all continents, resulting in the modification of the physical space where species grow and interact, and triggering biological responses which may lead to biotic collapse (Montoya, 2008). However, there is evidence that not all species decline to extinction in the same way due to habitat destruction; in fact, some species are at a greater risk in fragmented landscapes than others (Henle et al., 2004), depends on the species habitat preference and disturbance frequency (Mestre et al., 2020). A significant portion of this variation could be explained by the primary seed dispersal mode: species with morphological adaptations for animal dispersal are less vulnerable than species which are morphologically adapted for wind dispersal (Johst et al., 2002). Moreover, it is now clear that forest fragmentation has been the cause of biotic changes, and it is related to one of the most serious threats to biodiversity (Laurance et al., 2007).

The environmental impacts associated with mining are widespread in the Neotropics, with high concentrations of mining ore extraction extending from Central America to the Andean Ranges and South America. An example of metal mining pollution has been recorded in stream ecosystems in countries like Mexico and Bolivia (Razo et al., 2004; Espinosa-Reyes et al., 2014).

Most of the forests of the Guianas in South America are classified as seasonal evergreen forests or seasonal wet forests, and they are reported to have a large

percentage of forest cover and low deforestation rate: 87.5% for Guyana (Dewnath et al., 2020); 93% for Suriname (Zalman et al., 2019), and 90% for French Guiana (Richard-Hansen et al., 2019). Specifically in Guyana, the rate of tropical deforestation is low when compared to other South American countries (Lowe, 2014). An examination of the Forest Reference Emission Level for Guyana showed a mean annual CO₂ emission rate of 0.049% from 2001 to 2012 (Government of the Cooperative Republic of Guyana, 2015). Alluvial mining, gold mining, and selective logging were the main drivers of forest emissions levels in Guyana. Furthermore, mapping higher resolution (5 m) RapidEye image showed that small-scale artisanal gold mining and its associated infrastructure constituted 97% of all forest loss in Guyana in 2014 (Pickering et al., 2019).

Publications with specific information about quantitative annual deforestation for bauxite mining in Guyana, however, are not available (Overman et al., 2019).

Each stage involved in bauxite mining has a negative impact. Bauxite mining operations are large-scale operations which require the removal of vegetation. This vegetation removal gives way to large forest clearing. The largest lateritic and coastal deposit of bauxite in the world is located in the Amazon Forest, the coastal areas of the Guiana Shield, and the Brazil Precambrian Cratons (bauxite mining is of great importance to the economy of these nations). Bauxite mining projects in the Neotropics are concentrated in Brazil, Jamaica, Venezuela, Suriname, and Guyana (Monsels & van Bergen, 2017). Globally, most of the bauxite mining projects which are being executed in the tropical regions pose a significant threat to undisturbed forests and biodiversity hotspots (Mindszenty, 2016; Murguía et al., 2016). China and Malaysia have relevant experience in dealing with bauxite mining operations and environmental mitigation after mines are closed (Thorpe & Watve, 2015; Kuan et al., 2020).

In South America, plantation experiments of exotic vegetation have been used in different mines as rehabilitation techniques. For example, the colonization of native species has been successful in Minas Gerais in Brazil (de Almeida Silva et al., 2019; Balestrin et al., 2019) and in Los Pijiguaos in Venezuela (Mazón & Gutiérrez, 2016; Gordon et al., 2011). In Linden, Guyana, *Acacia* cultivation has been carried out; however, success in native plants' colonization still needs to be evaluated (Santini et al., 2015).

Two rehabilitation cases in bauxite mining in Minas Gerais, Brazil (Miranda et al., 2014) and Los Pijiguaos, Venezuela (Gordon et al., 2011) demonstrate the importance of nurse trees. These trees were planted as part of a restoration technique to facilitate the arrival of native species from the surrounding ecosystems. They germinated in different substrate conditions, and the identified dispersion syndrome enhanced post-mining restoration.

6. Post-Bauxite Mining Mitigation of Forest Degradation

The conditions for reclamation occur when bauxite mine dumps are considered stable in terms of erosion. Rehabilitation is the planting of tree species to aid in re-stabilizing a forest community which will aid in preventing further erosion.

Restoration is considered to occur when the original forest prior to mining is restored or at least some of the ecosystem functions has been attained (Figure 3). Physical restoration after bauxite mining involves levelling and topsoil replacement. Topsoil is collected from storage areas in close proximity to the reclamation site. The topsoil is placed above the bauxite mine spoils at specified depths. In order to encourage tree growth fertilization and amelioration may be considered this is dependent on the physico-chemical characteristics of the bauxite mine spoils.

Ecological restoration of degraded forested lands is the process aimed at reforestation, the principal objective of which is to restore the ecosystem to its former conditions. This means that the site will contain the original complement of plant and animal species, inclusive of its original structure, productivity, and ecological processes. The recovery process of deforested lands can be accelerated by reforestation. In this regard, it is important to note that there are several ways in which re-forestation can be carried out, with each pathway leading to a different outcome (Lamb, 2013). Reforestation may utilize both exotic and native species which would only partially restore forest structure and productivity. With silvicultural interventions, however, sometimes reforestation can exceed that of the original ecosystem, to the extent that there is increased forest cover (Lozano-Baez et al., 2019) and habitat complexity, thus resulting in overall recovery of the ecosystem (Borišev et al., 2018). Besides the two approaches lies a midway position that is commonly referred to as rehabilitation.

The goal of rehabilitation is to recover original forest structure and productivity, but not necessarily all of the original biodiversity. It is critical to assert that rehabilitation enables the establishment of a new ecosystem. This new ecosystem may contain a mix of native and exotic species and, over a period of time, it would gradually drift back to its original state (Lamb, 2013). Even though they share certain common attributes, their differences lie in the degree to which

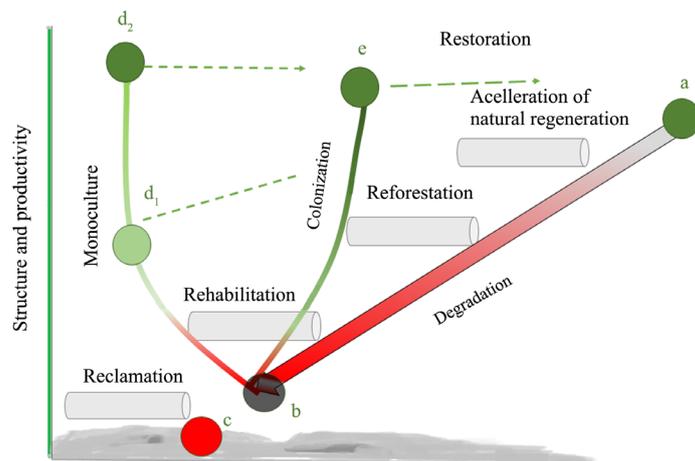


Figure 3. Various methods of reforestation after degradation. (a) Original Forest (b) Fragmented Forest (c) Degraded Forest (d₁ and d₂) Reforestation via Plantation Forest (e) Natural Colonization. (adapted from Lamb [2013]).

biodiversity is recovered (Chazdon, 2003). These include the achievement of a new, stable, productive land use (Wortley et al., 2013), and at least some recovery of the ecological services and protective functions of the original forest (Chazdon & Uriarte, 2016; Lamb, 2013).

Restoration efforts should be planned at the landscape level. The aim should be to reestablish ecological integrity, support human well-being (Millenium Ecosystem Assessment, 2005; Sabogal et al., 2015) and ensure a complementary protected area network to regain biodiversity restoration (Lamb, Erskine, & Parrotta, 2005). However, restoration ecologists are still debating the probability that disturbed forest ecosystems can restore themselves naturally, at a reasonable time, without human intervention (Prach, Šebelíková, Řehouňková, & del Moral, 2019).

For instance, post-bauxite mining restoration poses significant challenges, two of which are as follows: the reconstruction of the landscape, and the conversion of bauxite residue into soil; in fact, this soil may evolve slowly over a long period of time in order to regenerate a functional ecosystem (Macdonald et al., 2015).

Studies conducted in the ambit of restoration in post-bauxite mining lands have shown that plant colonizers, which are a form of passive restoration, can gradually provide a functional ecosystem (Holl & Aide, 2011).

Mining in the Neotropics, particularly in South America, has a long tradition. This tradition has generated areas of un-restored mined lands in sensitive ecological areas and in important river basins. However, the actual numbers and areas of mine wastelands are not well documented or updated. In Guyana, most of the studies conducted in the area of post-mining lands restoration have focused on determining which exotic species can restore gold and bauxite waste lands on a very small scale (Santini & Fey, 2013). Corbin & Holl (2012) report the importance of the method of applied nucleation which incorporates native and exotic species to optimize forest restoration. Traditional plantation experiments have also proven to be successful. One such example is that of an *Acacia mangium* Willd plantation in the St. Elizabeth gold mine in Mahdia (in Guyana) which regenerated after 7 years of passive restoration; however, and unfortunately, there are no publications about the natural colonization process. Studies in the field of forest restoration, focusing on the dynamics of passive restoration, should be conducted. Natural colonization reported in bauxite mine lands (Figure 4), without the aid of active restoration, should also be investigated. The success of post-bauxite mining restoration, particularly bioremediation, relies on planting fast-growing, light-demander and nitrogen-fixing species. These species act as a facilitator of the restoration process, accelerating the natural regeneration of native plant species, as in the case of the St. Elizabeth gold mining site. The restoration approach must be determined first, since this determination would inform restoration ecologists about two things: 1) the best approach and best practices to employ in the restoration of post-bauxite mining lands, and 2) the specific plant colonizers to use in the restoration process.



Figure 4. Active and Passive Restoration of Bauxite Residue (a) Tree Colonization (b) Mixture of Colonization of Trees and Grasses (c) Scrub Colonization (d) Mixture of Colonization Grasses and Scrubs (e) Active Restoration with *Acacia mangium* Willd (f) Natural Regeneration (Photos: Lorrimer Gordon, 2019).

Prior to the 1980s in Brazil, bauxite mine rehabilitation programmes involved reforestation with fast-growing exotics such as *Eucalyptus* spp. (*Eucalyptus camaldulensis*, *E. citriodora*, *E. pellita*, *E. torrelliana*, *E. urophylla*, Australian *Acacia* spp. (*Acacia mangium* Willd) and native species, such as *Bracatinga scabrella* Benth (Parrota and Knowles 1999). *Myrcia splendens* species of the Myrtaceae family was utilized in a restoration programme in Minas Gerais State, in south-east Brazil in 2013.

Brazil is the leading country for post-mining restoration research in South America (Guariguata & Ostertag, 2001). In 2016, for example, an assessment of the initial ecological succession after 5 months of topsoil deposition areas, degraded by bauxite mining in Serra da Brígida, Ouro Preto, and Minas Gerais, recorded 2028 plants (about 29 individuals per m²). These plants included species of commercial value, such as *Spermacoce capitata* (Ruiz & Pav.) DC; *Axonopus pressus* (Nees ex Steud.) Parodi; *Pleroma heteromallia* D. Don (D. Don);

Rhynchospora sp.; *Croton erythroxyloids* Baill; *Ageratum fastigiatum* (Gardner) R.M.King & H.Rob.; *Jacquemontia linarioides* Meisn; *Stachytarpheta glabra* Cham.; *Eremanthus erythroaappus* (DC.), and species of the MacLeish and Poaceae family. In general, post-mining restoration research in Guyana is low.

The development of ecologically based sound strategies for restoration, based on landscape ecology spatial tools and approaches, are the most appropriate to be followed in a spatially driven design plan for the restoration/reclamation of Bauxite Mine Lands.

The only study, in this regard, published by Santini & Fey (2013), suggested that high precipitation has facilitated vegetation establishment within the bauxite storage area in Linden (Figure 5). However, based on the data collected, the study cannot ascertain whether pH, electric conductivity and total alkalinity differed between vegetated and un-vegetated areas.

The first step in planning for the restoration of bauxite mine lands is an analysis of the chemical compounds and the physical characteristics of the residue. This is because bauxite residues differ based on their origin (Gräfe & Klauber, 2011). Additionally, residues do not contain soil organic matter—an unfavourable soil condition—because it generates very low microbial activity (Vilas Boas, Almeida, Teixeira, Souza, & Silva, 2018). Physical methods focus on improving soil structure and soil organic matter (Shu et al., 2005; Sheoran et al., 2010; Farrell et al., 2010; Festin et al., 2019). In abandoned bauxite mines, land slopes, elevation, aspect, and drainage are important components of landform which play a key role in the success or failure of restoration efforts (Zhang et al., 2011). For example, restoration in areas with steep slopes may be suitable only for grazing. Slopes with less than 2% grade are prone to flooding; furthermore, such slopes present a precarious situation: overburden dumps with cracks become unstable and bedrock dumps become unsuitable for planting (Bell, 2002; Sheoran et al., 2010).

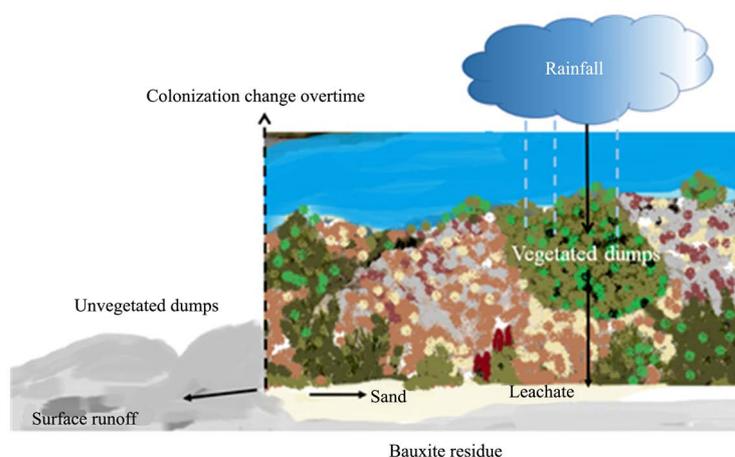


Figure 5. Simulation of plant colonization in bauxite residue as an indicator and facilitator of soil remediation (adapted from Santini et al., 2015).

Carlson et al. (2015) defined biochar as a by-product of combusting biomass for energy production. Biochar has been proposed as a soil amendment, and its application in bauxite residues improves the porosity and the water holding capacity of the soil. In addition, biochar adds nutrients to the soil and increases soil pH (which induces a higher electrical conductivity) (Lebrun et al., 2016). Biochar may mobilize and immobilize heavy metals and Arsenic by direct means, such as ion exchange, physical adsorption, and precipitation (Lehmann & Joseph, 2015; Beesley & Marmiroli, 2011). The purpose of physical methods in bauxite mine lands is to reduce soil compaction. Soil compaction reduction leads to enhanced soil properties which create suitable conditions for plant growth.

The uses of bauxite residue in bioremediation, such as structural fill and bank embankment, are impeded by the presence of Sodium Hydroxide (NaOH) and Sodium Carbonate (Na_2CO_3) (Panda, Jain, Das, & Jayabalan, 2016). Therefore, physico-chemical remediation of bauxite involves correcting soil pH, electrical conductivity, exchangeable sodium percentage, and bulk density. For example, Santini et al. (2015) suggested that a pH between 5.5 and 9.0, an electrical conductivity of $<4 \text{ mS}\cdot\text{cm}^{-1}$, an exchangeable sodium percentage of $<9.5\%$, and a bulk density of $<1.6 \text{ cg}\cdot\text{cm}^{-3}$ are values commonly observed in well-functioning soils.

Applications of various chemical and physical amendments to accelerate remediation and soil development in bauxite residue are not new. The aim of these applications is to reduce salinity, sodicity, and alkalinity, and to encourage soil structure development. For example, soil pH can increase by adding fertilizers (such as limestone) with a combination of biological amendments (Festin et al., 2019) (such as hay, mushroom compost, and sewage sludge). All of these biological amendments have been effectively improving soil chemistry and structure (Courtney, Mullen, & Harrington, 2009). Gypsum, a Calcium Sulphate ($\text{CaSO}_4\cdot 2\text{H}_2\text{O}$) from which sources of Calcium (Ca) and Sulphate (S) can be obtained, is used in combination with vermicompost as a soil ameliorant to improve some physico-chemical properties of bauxite residues (Chauhan & Ganguly, 2011).

Studies conducted have made use of non-indigenous and indigenous bacteria microbes, with dairy waste product, sugar molasses, and rice water as inexpensive sources of carbohydrate-rich nutrient, to lower the high alkalinity of bauxite residue (Panda et al., 2016; Zhang & Zang, 2016). Chemical methods have several limitations, some of which are as follows: high application cost, the addition of more toxic substances to the soil, and the potential for pollution of water bodies. As such, the use of vegetation and its associated microbes for bioremediation of mine lands is considered to be an effective path for the restoration of bauxite lands.

Restoration of mine soils requires the reconstruction of a specific environmental condition which is considered to be the greatest challenge for microbes, as it pertains to their survival and growth (Chodak & Niklińska, 2010). There-

fore, practical studies to recover some ecosystem functions (such as the nutrient cycle) are warranted, especially because of their usefulness for bauxite remediation strategies (Courtney, Feeney, & O'Grady, 2014). Biological methods (or phytoremediation) are a set of techniques which involve the use of green plants and their associated microorganisms to remove uptake and to immobilize contaminants in the environment (Oyuela Leguizamo, Fernández Gómez, & Sarmiento, 2016).

Soil remediation involves plants (phytoremediation) and microorganisms (rhizoremediation) which, together, are referred to as bioremediation (Estrada-de los Santos, Rojas-Rojas, Tapia-García, Vásquez-Murrieta, & Hirsch, 2016). In addition, microbial communities are associated with the composition of vegetation and soil structure (Hao, Leung, Wang, Sun, & Li, 2010); however, knowledge of the long-term growth and sustainability of vegetation and microbial communities on residue remediation is limited worldwide (Banning, Phillips, Jones, & Murphy, 2011). A recent conceptual model of the existing knowledge base and the specification of main research gaps for the beneficial contribution of bioremediation in bauxite residues were developed by Santini et al. (2015). A biochemical pathway is suggested for pH neutralization; for this to happen, however, a pioneer microbial community function would be required to determine threshold conditions, and overall remediation strategies would be necessary to locate areas where bioremediation is suitable.

Vegetation influences the composition of microbial communities and the physico-chemical characteristics of the soil (Jangid et al., 2011). The mutualistic relationship between plants and soil microbes depends on the availability of essential physico-chemical characteristics of the residue (Reynolds, Packer, Bever, & Clay, 2003). Globally, the identification and selection of plant species which can withstand poor edaphic and climatic conditions of bauxite residues is an on-going challenge (Seo et al., 2008). Hence, the success of the revegetation process depends heavily on knowing plant species (and the kinds of species needed for this purpose) which can form a mycorrhizal symbiosis. The use of plant species with a high dependency of Arbuscular Mycorrhizal Fungi (AMF) can improve the revegetation of post-mining areas (Sousa et al., 2014; Caproni et al., 2018).

Mycorrhizal Fungi symbiotic association provides benefits to plants from soil nitrogen and phosphorous uptake, and it also increases resistance to biotic and abiotic stress (Toju, Sato, Yamamoto, & Tanabe, 2018). It is useful to distinguish the ability of mycorrhizal fungi to form a specific association in bauxite mine lands. AMF is used as an amendment for plant growth, especially in nutrient-poor soils. AMF, if used as a forest inoculum, could accelerate the ecological restoration in below- and above-ground communities (Li et al., 2015). According to Wang (2017), most plants are colonized by AMF in metallic and other mine sites, and these sites have high numbers and multiple diversities of AMF species. Wang's review suggests that AMF species and their hosts may develop adaptive strategies which can be implemented on disturbed sites. The afore-mentioned au-

thor proposed a selection of AMF plant combination for restoration programmes. Mycorrhizal colonization affects the successional stages of species and the structure of plant communities; similarly, vegetation has a significant effect on the fungal community. Sousa et al. (2014) stated that the greater richness of AMF species is found in the late stage of succession. The identity of initial colonizers and their tolerance are currently unknown; owing to this, an evaluation of the microbial inoculant “bioaugmentation” process for supporting succession is necessary (Santini et al., 2015). For example, research has found that the scrub legume *Periandra mediterranea* (Vell.) Taub is a potential plant for bioremediation of bauxite degraded areas in the Campo Rupestre Grasslands of Brazil.

Even though areas affected by mining may have different species of plants, and although the richness of plant species which colonize those areas may vary, it is clear that they are dominated by certain taxonomic or functional groups. Therefore, even if there may be substantial differences in the richness of plant species among mines, within and amongst localities, differences in taxonomic rank of groups (genera and families) tend to be low, especially in the early succession stage.

The different aspects highlighted above strongly suggest the importance of identifying how the different phases of colonization can be affected by substrate conditions. What must be taken into account is that the presence of plant communities in a particular place does not depend solely on the quality of the site, but also on the possibilities of species dispersal and their potential for germination, survival, and establishment (Reid & Holl, 2013). Mitigation of bauxite mining and forest land restoration must take into consideration the landscape level and how the richness of plant species relates to soil development. Soil remediation and microbiological dynamics, especially the influence of AMF, seem to play an important role in the colonization in areas affected by mining.

7. Conclusions and Recommendations

Despite the years of bauxite mining in the Neotropics (particularly in Brazil, Jamaica, Venezuela, Suriname, and Guyana), no systematic review has summarized the restoration practices of forested lands under bauxite mining in these countries nor highlighted the environmental impacts associated with wastelands. From a global perspective, this review found that scientific, empirical studies which evaluated the success of ecological restoration were low in South America (4%) and Tropical Africa (3%), especially when compared with North America (46%), Oceania (23%), Europe (14%), and Asia (10%) (Wortley et al., 2013). So far, most of the research in the Neotropics has been conducted in the moist and wet lowland forests, including the Atlantic Forest of Brazil, Venezuela, and Guyana.

Gold mining is threatening South America’s forest resources. Restoration of waste lands is thus critical in the fight to decrease erosion of forested lands since it has local effects on the riparian systems and on the livelihood of the local

communities who inhabit the river watershed affected. This situation requires the optimization of restoration practices in order to conserve the remaining moist tropical forest biodiversity.

The literature review has shown that Brazil is the leading country for post-mining restoration research in South America. Between 2001 and 2006, forest changes for Guyana were reported by drivers which singled out mining in general, and mining infrastructure, as the foremost contributor of deforestation. Percentages of deforestation due specifically to bauxite mining, however, have not been reported. Currently, two large-scale Russian-owned Bauxite operations are working at Linden and Kwakwani, and one new Canadian operation at Bonasika (Laing, 2019). The contribution of bauxite mining to deforestation and land degradation in Guyana is unknown, and this state of affairs is similar to other bauxite-producing countries in South America. Besides this, the numbers and area size of closed and active bauxite mines, the age of bauxite storage areas (overburden dumps), and their status, among other much needed information, are not well documented. What's more is that the changing in ownership of bauxite mining companies leads to working back mine areas that were once closed (making them active again). Data on the age of bauxite overburden dumps are extremely important for soil chemical and physical monitoring and restoration (Courtney et al., 2009).

Three recommendations derived from the different studies highlighted in this review are as follows: 1) use a landscape approach in the study of the areas to be restored or remediated, since it allows for an understanding of what drives the spatial distribution of the native restoration processes; 2) conduct a thorough inventory of the colonizer species in different landscapes, as it relates to the soil conditions both at the chemical and microbiological levels, and 3) analyze the potential of using biochar in the restoration process.

This literature review synthesizes the potential of landscape restoration as a pathway for reversing or minimizing forest loss and forest degradation due to bauxite mining in South America, particularly in Guyana. In this country, recent investments in the mineral industry come with greater pressure on the government to increase and allocate concession areas in the remaining pristine forests. It is therefore imperative to conduct scientific research in forest land restoration (FLR), with the aim of filling the information gaps in forest biodiversity conservation, and with the objective of identifying colonization models and succession as the key drivers of FLR in bauxite mine lands.

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Conflicts of Interest

The authors declare that there are no conflicts of interest.

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