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Vegetating mine tailings: The benefits of using non-native species in the remediation of a bauxite residue site in Jamaica

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Abstract

The impact of non-native plant species, particularly invasive species, on biodiversity has been investigated and documented for decades and the general consensus is that they can pose risks and have a negative effect on native flora and fauna. However, there can be ecological and conservational benefits from using non-native plant species in the mine closure process, where remediation of process waste within a defined time period is often a requirement and presents greater challenges compared to a normal mine site.

Initial remediation work on Rio Tinto's bauxite residue sites in Jamaica commenced in the mid-2000s, and with the majority of the vegetation work now completed this paper aims to present some of the advantages of using non-native species in the remediation programme undertaken at a bauxite residue disposal site. In addition, the paper discusses the use of non-native plants in mine closure projects generally, local challenges surrounding the awareness and management of species that are now considered invasive, and some direction when local legislation is absent.

The aim of this paper is to offer another perspective to the general view of negative impact of non-native species and demonstrate how some non-native, and even invasive plants, could play a beneficial role in certain cases in the field of tailings site closure.

Keywords*: mine closure, mine tailings, bauxite residue, red mud, revegetation, non-native species, invasive species, biodiversity*

1 Introduction

Revegetation is a typical mine closure objective aimed at increasing environmental quality post mining by minimising fugitive dust, providing a clean surface layer to reduce pollution from rain runoff, and stabilising embankments, as well as restoring the land to a form close to its original state. However, it can be a very challenging objective where mine tailings are concerned, due to the various characteristics of metalliferous waste that limit plant growth (Tordoff et al. 2000; Xue et al. 2016; Wang et al. 2017). Often, quick vegetative establishment and growth is required to control erosion (Sheoran et al. 2010) and dust (Tordoff et al. 2000), and in some cases to be able to survive adverse weather conditions such as droughts and hurricanes (Williams et al. 2022). Such revegetation projects require fast growing plant species that can survive the harsh conditions they are exposed to and form a diverse and sustainable vegetative cover.

Apart from a plant's ability to grow rapidly under hostile conditions, there may be other aspects that require consideration when selecting suitable plant species for growing on mine wastes. These considerations include compatibility with restoration targets (Skousen 2010), functional traits necessary to encourage establishment of other organisms, number of species needed to optimise restoration success, and a species' origin (Gastauer et al. 2017). The latter poses limitations to planting non-native species (also known as introduced species).

The objections against using non-native species (whether a regulatory obligation or best practice) is understandable. Introducing non-native species into a new environment is not without risk as it could outcompete native species and ultimately cause harm to ecosystems, economies, and/or human health (Pyšek et al. 2020). Such species are often referred to as 'invasive' and there are many publications outlining their negative impacts, with an estimated economic cost of over US$ 26 billion per year in North America alone (Crystal-Ornela et al. 2021).

However, the general negative attitude towards non-native species has also received a large number of opposing views in recent decades and has led to a demand for a more holistic and unbiased approach towards such species (Davis 2009; Davis et al. 2011; Cassini 2020). For example, Davis et al. (2011) pointed out that many claims of the detrimental threats posed by introduced species are often not supported by data and that using terminology to describe species introductions, including "biological pollution" and "alien invasions" (Lowe et al. 2000; Elliot 2003), only strengthens the message that "introduced species are the enemies of man and nature" (Davis et al. 2011).

Nowadays, most scientists seem to agree that non-native species can cause changes to an ecosystem, but the exact impact of most introductions is still poorly understood (Jeschke et al. 2014; Cassini 2020, Reise et al. 2023). Despite the overwhelming focus on prolific invasions in the literature, most introductions of non-native species are not actually expected to result in invasions (Kowarik 1995). Biological invasions can present a major threat to the diversity of natural systems and the ecosystem in a particular region if not carefully considered. However, various studies show that invasive species in one area may not be invasive in other areas, indicating intraspecific variation in invasion success (Zenni & Nuñez 2013). Though highly unpredictable, a species invasion seems to be more of a worst-case scenario rather than a fixed result of a species introduction.

The scientific community has mainly reported on the negative impacts of non-native species such as loss of biodiversity (e.g. Pyšek et a*l*. 2010). However, in recent decades many non-native species (including invasives) have been described as beneficial in a wide range of studies where they may play a positive role as providers of habitat, shelter, and food for native species, catalysts for restoration, ecosystem engineers, and performers of ecosystem services (Schlaepfer et al. 2011; Sax et al. 2022). Some non-native species have been reported to have potential conservation value, especially considering possible advantages of introduced species to an ecosystem in its journey of adapting to climate changes (Reise et al. 2023).

Though non-native species could be beneficial in mine closure projects, very little information has been presented with regards to such cases. In this article the authors would like to share observations from a remediation project in Jamaica, where over 30 ha of bauxite residue was successfully vegetated with mainly non-native plant species. The complete remediation project involved dewatering, reprofiling, mechanical conditioning of the residue, addition of amendments and then finally the vegetation phase of the work. It should be noted that the intention of this paper is not to encourage casual introductions of non-native plant species in mine closure projects. However, a best practice approach excluding non-native plant species, leaves little room for innovation and suggests a one-size-fits-all method. More importantly, it also does not consider whether a non-native or invasive species is already present in a given area or country, thus nullifying the risk associated with introducing a species.

Though native plants are preferred over non-native plants, there may be various reasons to consider planting non-native species in cases where the native ones cannot meet the closure objectives. Rather than ruling out a species based on its origin, it is recommended to explore potential options to benefit from the use of non-natives in challenging revegetation projects, by allowing for some flexibility and evaluating plant species on a case-by-case basis.

As such, the paper presents some of the important benefits of non-native plants as observed during the bauxite residue site remediation project in Mount Rosser in Jamaica and also highlights some considerations with regards to the use of such plants, supported by practical examples as experienced during the revegetation phase of the project.

2 Background

2.1 General

Bauxite remains one of Jamaica's most exploited natural resources, generating employment, economic uplift, as well as community and infrastructure development across the island. Knowledge of the existence of the bauxite deposits in Jamaica dates back to the 1860s. Alcan, a prominent mining company, initially exported bauxite and then built two aluminium oxide production refineries; the first near Mandeville known as Kirkvine in 1952 and a second near Ewarton in 1959. The refineries progressively expanded and ultimately had a production output of approximately 550,000 tonnes per annum of aluminium oxide (alumina). Both refineries manufacture aluminium oxide from bauxite using the Bayer process starting from bauxite. The Bayer process relies on conditions of high temperate, high pressure and strong alkalinty. During the process, approximately 1.5 tonnes of a waste product, called bauxite residue (sometimes called red mud), is generated for every tonne of alumina produced. Until the mid-1980s, the normal practice was to discharge the residue as a slurry containing typically 20% solids into lagoons or dammed areas (Evans 2016). This was the practice in both Ewarton and Kirkvine and each factory generated approximately 600,000 tonnes of bauxite residue every year.

Ewarton was the first plant in the world to adopt an improvement of this system, called dry mud stacking, which produced a high solids residue and enabled the residue to be stored in a semi-dry state with a solids content of up to 35% (Evans 2016). This practice has subsequently been adopted globally and remains the primary method for disposal, although the use of press filters is increasingly being adopted (Avery et al. 2022). As a results of these early operations some 13 bauxite residue areas at Kirkvine and a large deposit adjacent to Ewarton at Mount Rosser needed to be remediated.

In 2001, Alcan sold its bauxite mining and alumina plants in Jamaica but kept the responsibility for many of the bauxite residue sites with the intention of safely remediating them and returning ownership to the Government of Jamaica (GoJ). In 2007 Rio Tinto plc/Rio Tinto Limited acquired Alcan Inc. and responsibilities for the remediation were passed to Rio Tinto plc.

2.2 Closure plan

Following the sale of the operating assets, in 2004 Alcan initiated a review of possible remediation strategies for both Kirkvine and Ewarton to ensure adherence to all relevant standards were being met.

Initially, desk reviews of historical, geological and hydrogeological information, as well as chemical analyses of the residue, tracer studies, dam assessments, drilling trials and water/soil assessments studies were done. These were complimented by internal option reviews in addition to extensive discussions with the key regulators in Jamaica facilitated by the Jamaica Bauxite Institute (JBI). Other parties involved were: Water Resources Authority (WRA); National Water Commission (NWC); National Environmental and Planning

Agency (NEPA - NRCA); Commissioner of Mines (CoM); Commissioner of Land (CoL) and the Environmental Health Unit of the Ministry of Health (EHU-MoH). Following multiple rounds of reviews, the final closure plan was signed off in 2006 by all regulators listed above before work commencement.

The overall closure objective was to establish 70% vegetative cover that would be sustainable, diverse and would require minimum future intervention. Additionally, a site investigation and botanical survey were to be carried out to show that the ground did not contain concentrations of elements or chemical species that could cause adverse harm to grazing animals or represent a significant risk to humans if ingested; the investigation and survey needed to show that the area could be substantially covered by plant species that could not cause adverse harm if consumed by any animal.

In collaboration with JBI, the University of the West Indies (UWI) and the Jamaican Science and Research Council, extensive vegetation trials were done on the bauxite residue in Kirkvine in the early 2000s. In the studies, various organic treatments and gypsum application rates were evaluated to ascertain a suitable *in situ* topsoil free planting medium. Plants considered for extensive trials were selected based on local availability and potential ecological benefits and the species found to grow readily in the local area were: Bermuda grass (*Cynodon dactylon*), Guinea grass (*Megathyrsus maximus*), brachiaria grass (*Brachiaria decumbens*), leucaena (*Leucaena leucocephala*), bona vista bean (*Lablab purpureus*), and castor bean (*Ricinus communis*) and were used for subsequent work at Kirkvine and formed the basis of the work at Mount Rosser. Species selection was done based on a plant's performance on the conditioned bauxite residue, local availability, and potential ecological benefits. Utilisation of native species was not a priority when the remediation strategy was designed. Though native plants were considered, they did not meet the criteria that was targeted. As such, the plant mix consisted predominantly of non-native species.

2.3 Mount Rosser Bauxite Residue Deposit Area Revegetation

The revegetation part of project for Mount Rosser's Bauxite Residue Deposit Area (BRDA) (coordinates: 18.20956, -77.09094) started in 2016 with the original planting programme. A few years later, several species were added to the planting programme in order to augment the areas prone to flooding and water logging. As a result of this, vegetation on the site can now be divided into two distinct areas, the first containing the original plant species and the second area containing mainly wetland species (see Figure 1).

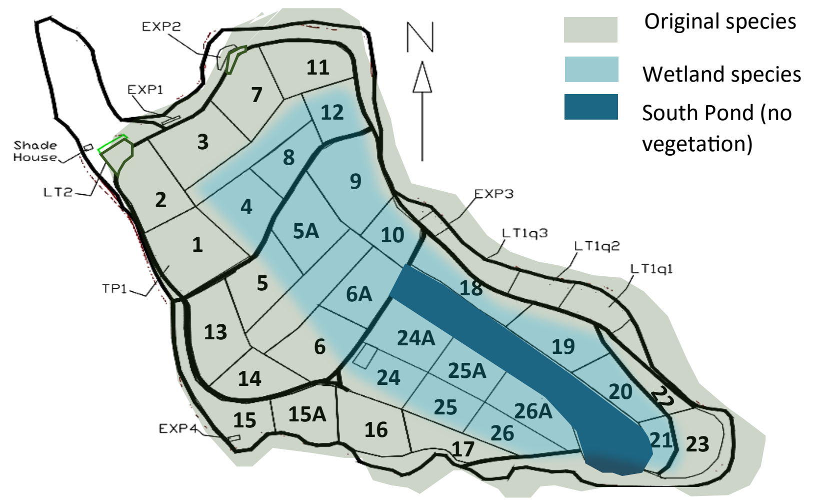


Figure 1 **Map of the 37 ha site in Mount Rosser showing the various vegetated fields with original plant species at the outer edge and wetland species towards the middle of the site where areas are prone to flooding and waterlogging**

The site was engineered to slope towards the South Pond, making the field towards the middle susceptible to flooding and waterlogging. This required more tolerant plant species able to survive after submersion in water following a tropical rainstorm or hurricane. Over thirty water tolerant plants were explored on the site of which only five were able to survive field conditions (Table 1). A species was judged to have 'survived' if it didn't die within two weeks after the site had been submerged under water following tropical rainstorms. Some species were planted to test their performance. In addition, various invasive species have been observed that were not planted but voluntarily migrated to the site. These species include logwood, (*Haematoxylum campechianum*), African tulip (*Spathodea campanulata*), and wild hop (*Flemingia strobilifera*).

Table 1 gives an overview of the species in both the original and wetland planting programmes with an indication of whether the species is a non-native and/or invasive species in Jamaica, as defined in the National Invasive Alien Species Strategy & Action Plan (NIASSAP) published in 2014. It should be noted that Table 1 does not provide a complete overview of all species planted on site. Some species were planted on a very small scale to test their performance. In addition, various invasive species have been observed that were not planted but voluntarily migrated to the site. These species include logwood, (*Haematoxylum campechianum*), African tulip (*Spathodea campanulata*), and wild hop (*Flemingia strobilifera*).

Table 1: List of plant species in the original and wetland planting program

	Scientific name	Common name	Native/Non-native	Invasive
Original species	*Brachiaria decumbens*	Brachiaria grass	Non-native	Yes
	Calliandra calothyrsus	Calliandra	Non-native	No*
	Cynodon dactylon	Bermuda grass	Non-native	No
	Lablab purpureus	Bona vista bean	Non-native	No
	Leucaena leucocephala	Leucaena	Non-native	Yes
	Megathyrsus maximus	Guinea grass	Non-native	Yes
	Ricinus communis	Castor bean	Non-native	No
Wetland species	*Arundo donax*	Giant reed	Non-native	No
	Brachiaria mutica	Para-grass	Non-native	No
	Casuarina equisetifolia	Whistling pine	Non-native	Yes
	Paspalum vaginatum	Salt water couch	Native	No
	Thespesia populnea	Seaside mahoe	Non-native	No

* *C. calothyrsus* is currently under review by the Jamaican National Environmental Planning Agency (NEPA) and is expected to become listed as invasive in the near future.

The invasive species as presented in Table 1 were not defined as invasive in Jamaica until after the project had commenced and approved by the government regulators.

3 Benefits

3.1 Fast growth

Perhaps one of the most obvious benefits of the non-native vegetation on the site was their performance on the conditioned bauxite residue in terms of survival and growth. The planting programme started in 2016 with small experimental plots when there was no vegetation on the site (similar to Figure 2a) and consisted of mainly non-native species. The vegetative cover increased rapidly during a six year period (planting finished in 2022), with a total of 78% coverage in June 2023 (see Figure 2b).

(a) (b)

Figure 2 Two images of Mount Rosser's Bauxite Residue Deposit Area: (a) The site without vegetation in 2014; (b) The site with 78% vegetative cover in June 2023

A drone (DJI M300 RTK with P1 sensor) was used to capture the image as presented in Figure 2b and ArcGIS Pro Version 3.1.2. was used to calculate vegetative cover on the entire site (including structures, roads, and water bodies) by manual segmentation of vegetation using the RGB values for pixels.

3.2 Biodiversity enhancement

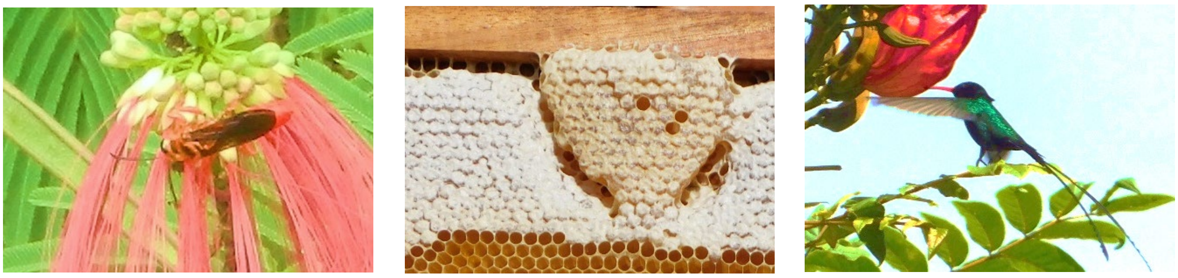
An example of a successful land reclamation strategy, is one where the initial choice of plant species encourages other species to become established but does not necessarily survive in the long term. The presence of non-native species on the site has helped to facilitate the establishment of many other species, including pollinators and birds.

3.2.1 Pollinators

Animal enabled pollination (by invertebrates, bats, and birds) is a critical ecosystem service (Kearns et al. 1998; Porto et al. 2022) and it is thought that up to 94% of wild flowering plants on earth depend on this type of pollination for reproduction (Vanbergen et al. 2013), emphasising the importance of pollinators to an ecosystem.

Non-native plants on the Mount Rosser site have attracted a wide range of pollinators including native and endemic species of bees, wasps (see Figure 3a), butterflies, and hummingbirds. The most popular attractants are the flowers of calliandra (*Calliandra calothyrsus)* and invasive African tulip (*Spathodea campanulate)*, which provide reliable and easily accessible sources of nectar and pollen when in bloom. In addition, capped honey cells from a bee brood box on the site (established from a wild swarm, discovered in a safety cone and later relocated to a brood box) showed honey made up of nectar collected from the invasive *Haematoxylum campechianum* flowers (see Figure 3b). Jamaican logwood honey is popular locally and overseas due to its consistency, clear colour, sweet taste, distinct flavour, and purported medicinal properties.

Many butterfly species have been observed visiting the vegetated fields, especially between November and January when many of the non-native species are flowering. During this period in 2019, a total of 16 butterfly species were observed, including two endemics. This was a remarkable finding seeing that only 66% of the site was vegetated at the time (Williams et al. 2022).



(a) (b) (c)

Figure 3 Three pictures showing the presence of different pollinators using non-native plants as food source: (a) The Jamaican digger wasp (*Sphex jamaicensis*) feeding on nectar from *Calliandra calothyrsus*; (b) Capped cells with the lighter colour containing bee honey produced from invasive *Haematoxylum campechianum* flowers; (c) Red-billed streamertail (*Trochilus polytmus*) feeding on nectar from invasive *Spathodea campanulate* flowers

Hummingbirds make up another important group of pollinators and they have been observed visiting flowers of non-native plants on the site. Frequent visitors include the Jamaica mango (*Anthracothorax mango*) and red-billed streamertail (*Trochilus polytmus*) (see Figure 3c) which are both endemic species with the latter being the national bird of Jamaica.

3.2.2 Birds

Birds are valuable indicators of species richness, as they are relatively easy to spot and identify. In addition, information is readily available on most bird species. Jamaica's avifauna is composed of about 307 species of which 127 are breeding species and 180 are migrants. A total of 30 endemic bird species can be found in Jamaica (Haynes-Sutton et al. 2009).

The many non-native plant species on the site attract a wide range of bird species, including hummingbirds as mentioned in the previous section, which directly and indirectly benefit from the non-native vegetation on the site. Two species listed as Near Threatened by the IUCN that are frequently found on the site visiting non-native tree species, including the olive throated parakeet (*Aratinga nana*) (see Figure 4a) and white-crowned pigeon (*Patagoienas leucocephala*).

(a) (b) (c)

Figure 4 Three pictures showing the presence of different bird species using non-native plant species: (a) Endemic and near threatened olive throated parakeet (*Aratinga nana*) in *Spathodea campanulate* tree; (b) Endemic orange quit (*Euneornis campestris*) feeding on nectar from *Calliandra calothyrsus* flowers; (c) Bird nest in *Haematoxylum campechianum* tree made of *Megathyrsus maximus* leaves

A wide range of native granivores and nectivores feed directly on the abundance of flowers and seeds of non-native plants (see Figure 4b) and some plants also provide nesting spots and material for several bird species. *Haematoxylum campechianum* for example, which is listed as invasive in Jamaica, is a very popular nesting spot amongst the native yellow-faced grassquits and bananaquits; they prefer small tree species with thorns which offers some protection against predators. The same species also build their nests from the leaves and flowers of the invasive grass *Megathyrsus maximus* and petioles from *Calliandra calothyrsus* leaves (see Figure 4c).

(a) (b) (c)

Figure 5 Three pictures showing the presence of insectivorous birds: (a) Endemic sad fly catcher (Myiarchus barbirostris) found frequently on the site hunting for insects; (b) Nest of Northern mockingbird (Mimus polyglottos) with 3 fledglings; (c) One of many nests on the site belonging to the cave swallow (Petrochelion fulva)

The vegetation on the site encouraged the establishment of a lot of insects, which in turn attract many insectivorous bird species that use the site as their habitat like the sad fly catcher (*Myriarchus barbirostris*) (see Figure 5a), Northern mockingbird (*Mimus polyglottos*) (see Figure 5b) and cave swallow (*Petrochelidon fulva*) (see Figure 5c).

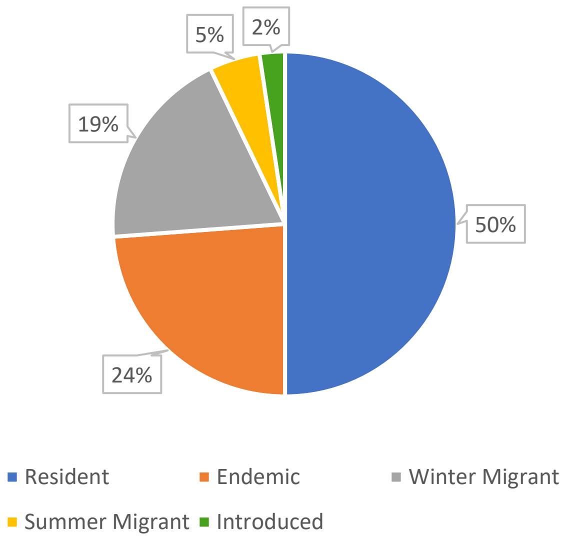


Figure 6 Distribution of bird species (42) observed on the site between 2018 and 2022

The mainly non-native vegetation on the site has created a habitat for the over forty bird species which have been observed on the site between 2018 and 2022, including ten endemic species. Figure 6 shows the distribution of all bird species on the site (with a total of 42 species). It should be noted that species that were observed, but could not be identified, are not included in Figure 6 and the total number of bird species is expected to be higher.

The various bird species were observed during field work whilst the planting project was ongoing. As this project has now finished, biodiversity surveys will form an essential part of the monitoring plan moving forward.

3.3 Soil quality improvement

When produced, the bauxite residue lacked nutrients and organic matter, had poor drainage and aeration, the liquid associated with the bauxite residue (termed liquor) had high pH (up to 11.7) and sodium levels (5 g/L and higher); these factors combined to make it hostile to almost all life forms. This was partially resolved by improving its structure by mechanical workings and the application of gypsum and poultry manure amendments (Williams et al. 2022), thus creating a medium that was more suitable for initial flora and fauna growth. However, to be sustainable, long term biological activities and nutrient recycling in the residue was essential. Plant species were evaluated and selected that had the potential to continue improving the soil quality after planting. Consideration was given to plant species that could form symbiotic relationships with mycorrhizal fungi, nitrogen fixing bacteria, and plants that produce substantial leaf litter. The species which fit most, or all, the categories and were readily available, fall under the non-native umbrella, including *C. calothyrsus, L. purpureus, L. leucocephala, C. equisetifolia.* The activities of these species add organics, attract biological life, and add nutrients to the residue that encourage vegetative growth. It can be argued that with better drainage, aeration, organic matter, and nutrient availability, the activities of plant roots and soil organisms ultimately continue to lead to improvements in soil quality over time.

(a) (b) (c)

Figure 7 **Three different tree species on the site with root nodules: (a) Root nodules in L. leucocephala; (b) Root nodules in C. equisetifolia; (c) Root nodules in L. purpureus**

Though no experiments were carried out to prove their effectiveness in terms of adding nitrogen to the soil, inspection of root systems of several plant species did reveal the presence of nodules in which bacteria can convert atmospheric nitrogen into nitrogenous compounds (see Figure 7). This plant characteristic was deemed essential when selecting plant species for the remediation project in Mount Rosser considering the fact that the bauxite residue generated from the Bayer process is completely devoid of any organic carbon of any nitrogen compound.

Another way various non-native plant species contributed significantly to improving the quality of the soil is through the production of litter. This is considered a critical pathway for nutrients to return to the soil (Krishna & Mohan 2017). Though all plant species produce some level of litter, *C. calothyrsus* produces most in the form of leaves, pods, seeds, and sticks; this is illustrated particularly well in Figures 8a and b.

(a) (b) (c)

Figure 8 **Three pictures showing litter in the field: (a) Litter from C. calothyrsus; (b) Litter from C. calothyrsus with species of fungus and beetle; (c) Litter from C. equisetifolia with seeds (of C. calothyrsus) emerging under the layer of litter**

Apart from nutrient cycling, the layer of litter provides many other benefits in the field, as it offers a cool and moist environment for seeds to germinate (see Figure 8c) and it reduces the dust levels in areas with little grass by covering the top layer. Litter also facilitates the establishment of many soil organisms, especially fungi and detritivores, both vital for nutrient cycling and decomposition processes (Eisenhauer et al. 2018).

An important group of detritivores found in high abundance in the various fields include the millepedes (Diploda class). Not only do millipedes play an important role in decomposition processes by feeding on organic debris (Coleman et al. 2004), they also indirectly affect microbial activity in the soil (Wang et al. 2018).

(a) (b) (c) (d)

Figure 9 Four different species of millipedes found in the soil and leaf litter: (a) Anadenobolus monilicornis; (b) Orthomorpha coarctata; (c) Unidentified species of millipede; (d) Bristly millipede (order Polyxenida)

Figure 9 shows some of the different species of millipedes found in the soil and the litter layer on the site which have been observed in all fields.

3.4 Erosion and dust control

The soil remediation method used for the project in Mount Rosser required extensive mechanical workings in order reduce the high pH of the residue by accelerating the carbonation rate of the soluble sodium species present such as sodium aluminate, reduce the moisture content and improve the structure of the bauxite residue by increasing porosity. The bauxite residue has a significant fine fraction, median particle size distribution of approximately 4 µm, and it is important to minimise dust generation during the dry season. In addition, a lack of vegetation made the 40 cm conditioned soil layer (containing amendments like gypsum and chicken manure) very prone to water erosion during the rainy seasons (see Figure 10a). As such, several fast-spreading non-native plant species were selected that could reduce the effects of water erosion and control dust generation.

Before the vegetation was established, the bauxite residue had no cover and was exposed to the elements. Whilst the residue remained moist and unrefined, limited dust erosion was observed; this changed when conditioning activities started (which accelerated during the drier months) where tractors mechanically dried out, broke up and refined the bauxite residue. A combination of finer particle size, increased mechanical activities, large exposed loose surface area, coupled with low precipitation led to serious dust generation (see figure 10b). Dust generation on many levels is undesirable, mainly because of health and safety concerns for the community.

(a) (b)

Figure 10 Soil erosion and dust generation on the site: (a) Rill erosion after heavy rainfall; (b) Dust generation when mechanically working the field

These factors needed to be minimised or eliminated as fast as possible for the sustainable long-term success of the project. The long-term solution involved vegetating these areas to provide a natural cover, reducing both water and wind erosion. The challenge was to find species that are both fast growing and can tolerate fluctuations in sodium levels and pH conditions. Only a limited number of species were found to be suitable, and most fell under the non-native category. As such several fast-spreading non-native plant species were used to reduce erosion, control dust pollution, and establish quick vegetative cover.

Before tree and shrub species had developed enough canopy to protect the surface layer, various grass species provided the protective function as they were readily available and their growth was phenomenal (see Figure 11). During the initial stage of the revegetation phase of the remediation project, Guinea grass (*Megathyrsus maximus)*, brachiaria grass (*Brachiaria decumbens*) and Bermuda grass (*Cynodon dactylon*) were used for this purpose and were proven to be effective in Kirkvine. These three species, however, performed poorly in flood prone areas and in 2019, para-grass (*Brachiaria mutica*) and salt-water couch (*Paspalum vaginatum)* were added to the planting programme in flood prone areas. African star grass (*Cynodon plectostachyus*) is a non-native volunteer species that formed quick and dense vegetation in generally poor performing areas.

(a) (b)

Figure 11 Rapid development of vegetative cover: (a) Field 1 and 2 before planting; (b) Field 1 and 2 approximately 3 months after planting

Several non-native trees selected for the planting programme on the site, which have reportedly been used to control erosion include *L. leucocephala*, *C. calothyrsus,* and *D. regia* (Bageel et al. 2020; Muoni et al. 2020; Rojas-Sandoval et al. 2013). All species displayed fast initial growth on the site, however, tree roots generally grew sideways to remain in the 40 cm conditioned soil layer (see Figure 12). This could impact anchorage negatively depending on the species (e.g., taller species would experience a more negative impact compared to smaller species). It is speculated that perhaps the far stretching roots limited to the 40 cm topsoil layer, could increase the ability of the plant to hold the top residue layer together and thus reduce erosion of the conditioned soil layer.

(a) (b)

Figure 12 Horizontal root development of two tree species: (a) L. leucocephala; (b) Ricinus communis

3.5 Self sustaining

Plant species that are able to survive and adapt to the harsh conditions on the site (e.g., high pH, high sodium levels, high concentrations of potentially phytotoxic metals, drought, floods), were essential to achieving the necessary vegetative cover. However, the ability to reproduce is equally as important, as its shows promise for long-term continuation. Even though it is too early to determine if species are self-sustaining, many of the non-native species have started to show signs of sexual and asexual reproduction (see Figures 13a and b) and there are several species that have produced seeds that have germinated and resulted in healthy looking seedlings (see Figure 13c).

(a) (b) (c)

Figure 13 Signs of long-term continuation: (a) Prolific seed production in C. calothyrsus; (b) Asexual reproduction in Arundo donax; (c) Establishment of Thespesia populnea seedlings from seeds produced by mature trees

3.6 Resilience to adverse weather conditions

Traditionally, the weather pattern in the Caribbean has two distinct rainfall peaks: an initial peak between May and June and a more prominent peak between September and October (Chen et al. 2002). However, the effects of climate change have also been observed in the Caribbean, which include rising temperature, wider annual extremes, and enhanced heavy precipitation (Stephenson et al. 2014).

These changes in the weather pattern, more importantly changes in precipitation, have also been witnessed in Mount Rosser during different phases of the project. The unpredictability of the rainy/dry seasons presented a significant challenge for the vegetation. Figure 14 shows the actual rainfall on the site every month between 2019-2021 compared to the expected rainfall in the area. As can be seen from this figure, there were several months where the site experienced a lot more precipitation than expected and there were also periods of prolonged drought. For example, in 2020 the vegetation on the site experienced a six-month period without rain.

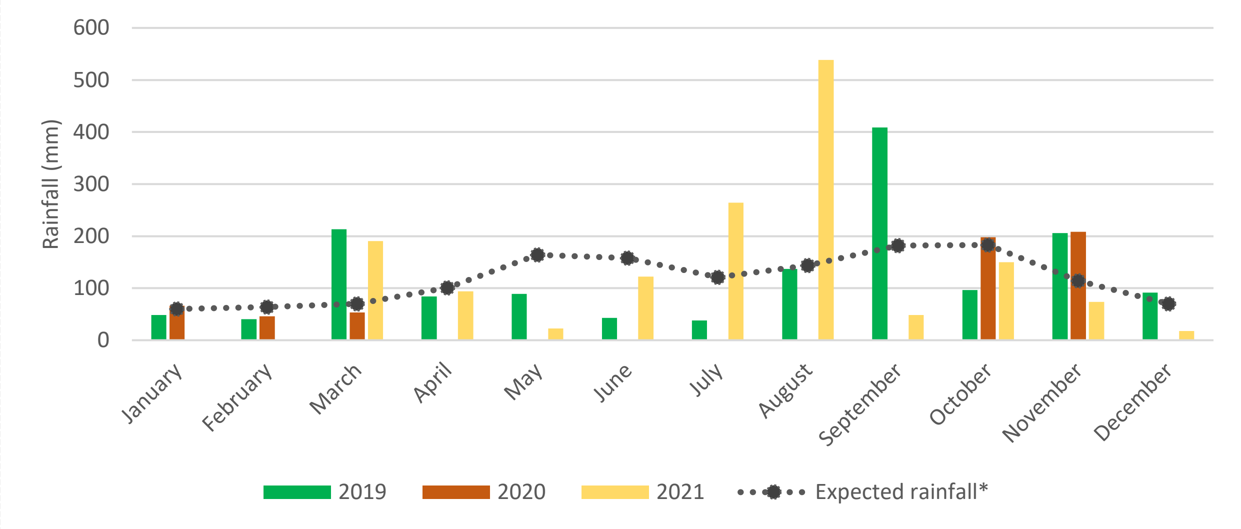


Figure 14 Actual rainfall vs expected rainfall per month between 2019-2021

*** Expected rainfall data is based on an average of rainfall in Ewarton (Alcan) St. Catherine between 1971-2000 (Meteorological Services Jamaica, 2021)**

The adverse weather conditions as illustrated in Figure 14 required resilient plant species able to survive heavy rainfall events (and flooding and waterlogging in some areas) as well as prolonged periods of drought. All species that were in the original planting programme were able to survive prolonged periods of drought, but most of those species were not able to survive flooding and waterlogging conditions, which occurred more frequently in the middle of site where the elevation levels are lower. As such, a separate planting strategy with different species able to survive flooding and waterlogging conditions, had to be implemented.

The strategy of increasing the diversity of plant species with more resilient species that can survive adverse weather conditions was incorporated into the Mount Rosser model. The most obvious benefit is the rapid recovery time of the vegetation after periods of drought/flooding as experienced during the planting project. Additionally, in the long-term, the approach may also increase the survival chance of the plant population whilst the country is experiencing the effects of climate change.

4 Native vs non-native

As highlighted in previous sections, there are a number of benefits to be derived from the planting of non-native plants, such as enhancing biodiversity, improving soil conditions, and reducing dust and erosion. Whilst native species are capable in providing many of the ecological benefits to the remediation project, there were a number of features where non-native species stood out from a practical point of view and this section aims to compare some of these features as experienced during the project in Mount Rosser.

4.1 Overall performance

Whilst most of the site in Mount Rosser bauxite residue disposal area has been vegetated with non-native plants, several native species were planted as part of a small experiment to test their performance on the site. Though some of the native species were successful, generally they showed a much slower initial growth rates and higher mortality after planting. For example, calliandra (*Calliandra calothyrsus)* showed a higher survival rate (75%) compared to blue mahoe (*Hibiscus elatus) (*38%). Similar findings were observed with other native forestry species, including Jamaican mahogany (*Swietenia mahagoni*) and West Indian cedar (*Cedrela odorata*), but accurate data was not recorded. The slow growth of forestry species also made them more susceptible to being smothered by other faster growing species, especially by volunteer species like African star grass (*Cynodon plectostachyus*) and bitter vine (*Mikania micrantha)*.

Whilst we have witnessed at Mount Rosser an example where some non-native species outperformed native species, it should be stressed that the data as presented above is not meant as evidence to prove that non-native species generally performed better in the field than native species. In fact, there were a few observations of native volunteer tree species in the field that performed quite well, including the trumpet tree (*Cecropia peltata*) and two unidentified species of ficus (*Ficus* sp.). It should be noted that the trumpet tree is an invasive species in many other countries and is on the list of the “World's 100 Worst Invaders”(Lowe et al. 2000). As *C. peltata* and the 2 *Ficus* sp.are volunteer species (not planted) and appear randomly (in terms of time and location), there is no data available on their survival rate.

Many of the successful volunteer species, however, are non-native. For example, from the eight volunteer grass species (Poaceae family) found on the site, only two are considered native. Both Pacific panic grass (*Panicum fasciculatum*) and whorled dropseed (*Sporobolus domingensis*) were found in newly planted fields, but were quickly outcompeted by other plants as they spread very slowly.

4.2 Availability of planting material

Another practical aspect to consider when comparing native with non-native species, is the availability of planting material. With “only” 37 ha of bauxite residue to revegetate, the site in Mount Rosser is relatively small compared to some other closure projects in the world. Yet still, with a planting density of 4,500 plants/ha for seedlings, 6,100 grass roots/ha for most grass species, and a seed mix that was broadcasted at a rate of almost 100 kg/ha (Williams et al. 2022), the project was in need of a great amount of planting material and relied heavily on local availability; this was a critical factor because of the remote and rugged nature of the site.

In order to obtain sufficient planting material for the project, seeds or seedlings needed to be either commercially available (e.g. Bermuda grass seeds and whistling pine seedlings) or planting material was harvested off-site (all other plant species), with the latter requiring abundant species in the environment that either produce a lot of viable seeds or provide other usable planting material such as roots. The widespread abundance of non-native species used for the project made it possible to plant an average of 9 ha/year.

5 Considerations

Using non-native plant species, including invasive species, in mine closure projects could add benefits to the (sometimes ambitious) goals of remediating closure sites. Invariably, native plants are preferred over non-native plants, however, there may be several reasons to consider planting non-native species especially in cases where the native ones are inadequate, limited, or cannot meet closure objectives. In such cases, there are some factors and ‘grey areas’ to consider when selecting species.

5.1 Risk of introducing an invasion

Perhaps the most important consideration surrounding non-native species, is the potential risk of introducing an invasion in an area or country. This risk is very unpredictable as invasion success or failure seems to depend on multiple factors such as propagule pressure, abiotic resistance, biotic resistance, genetic constrains, and mutualist release (Zenni & Nuñez 2013). However, this risk is normally only present if a non-native species is introduced to a new area, not if it is already present in the geographical region for a considerable amount of time.

We found that many non-native plant species (including some species listed as invasive) in Jamaica were introduced a long time ago. The first observation of *Megathyrsus maximus* in Jamaica for example, dates back to 1706 (Parson 1972), indicating that this species has been around for over 300 years before it officially became an invasive species. *M. maximus* is a well-known and popular livestock fodder in Jamaica (Paterson 1992) and a source of cheap and readily available mulch material for local farmers (Ministry of Economic Growth & Job Creation 2018).

Some non-native species are so well naturalised, to the extent that it is not always clear whether a species is native or non-native (Cassini 2020). Bermuda grass (*Cynodon dactylon)* for example has been described as a native grass species in Jamaica by Adams (1972), but more recent publications suggest that *C. dactylon* originated in Africa (Mitich 1989) and one paper mentions that it is an endemic species in Israel (Horowitz 1996), indicating some uncertainty as to its origin.

When considering non-native plants for any closure project, it is essential to investigate its presence in an area to avoid introducing a new non-native species.

However, any potential negative impact of a plant, whether native or non-native, on the project itself should not be overlooked. For example, a volunteer species called bitter vine (*Mikania micrantha*), was observed to smother and kill vegetation on the site. Though *M. micrantha* is native to Jamaica, it is considered invasive in many other countries causing severe damage to natural ecosystems and agricultural species (Zang et al. 2023). Their fast growth, resilience, and often adaptative nature, has its advantages, but without proper due process and management, could be very destructive for the overall vegetation strategy.

5.2 Conflict species

Several invasive plant species in Jamaica can be considered conflict species, where plants possess both useful and damaging attributes. *Leucaena leucocephala* for example, is listed as one of the “World's 100 Worst Invaders” (Lowe et al, 2000), but is often also referred to as a “miracle tree” as it is considered a valuable species in agroforestry, agriculture, and restoration projects (Olckers 2011; Bageel *et al*. 2020; Sharma et al. 2022).

This tree species also plays an important role in the Caribbean, which is likely the result of the “Leucaena project”, which was initiated at the end of the 1970s by scientist and energy experts in the Caribbean, exploring the use of *L. leucocephala* in agriculture and as an energy source. This was followed by the first International Conference on Leucaena in 1989 held in Trinidad and Tobago with the theme “Leucaena in Agricultural Development”, publishing numerous papers describing the many benefits of *L. leucocephala* ranging from animal feed to reducing soil erosion (e.g. Benn et al. 1992).

Similar conflict species in Jamaica include *Brachiaria decumbens* and *Megathyrsus maximus*. Despite their invasive status, the economic value to the local farming community remains significant and many government institutions in Jamaica continue to encourage farmers to establish these invasive species as livestock fodder.

5.3 Cause and effect

A lot of information is published on the impact of invasive plant species worldwide, but very little information is available on their impact in Jamaica. For example, *L. leucocephala* has been listed as invasive but there seems to be no data available showing the negative impacts in Jamaica. In fact, there seems to be no available data on negative impacts in the Caribbean, resembling the "guilty until proven innocent" approach towards non-natives, as introduced by Ruesink et al. (1995).

The Clearing House Mechanism (CHM) website (https://www.chm-cbd.net/about/chm) does state that a species can be classified as invasive if it is invasive on other islands with similar climatic conditions. Hawaii for example, classified *L. leucocephala* as highly invasive, but also lacks data to support its negative impact. In fact, due to its widespread distribution, especially on steep slopes, the priority to eradicate or control *L. leucocephala* is low and authorities prefer to focus on the control of species that actually invade and disrupt native ecosystems or threaten native species (Idol 2019).

Interestingly, Hawaii resembles Jamaica in other ways, apart from being an island with similar climatic conditions. Both have an expanding population and a shift towards tourism rather than the traditional farming, many degraded and disturbed lands have become available for *L. leucocephala,* a species with a preference for roadsides, wastelands, cultivated lands, riverbanks, and forest edges *(*Idol, 2019*).* This argument is in line with results from a study done by Rojas-Sandoval et al. (2017) who found that invasive species richness among islands in the West Indies, including Jamaica, is related to anthropogenic disturbance and economic development.

The above information raises an important question; if *L. leucocephala* is spreading in Jamaica, is this a result of invasive characteristics or an increase in the availability of ideal habitats? Such doubts with regards to cause and effect are not limited to the case of *L. leucocephala,* but various other invasive plant species in Jamaica that show preference for disturbed lands.

5.4 Regulatory guidelines

Jamaica's biodiversity is vulnerable to a variety of threats including the emergence of invasive species. In collaboration with overseas organisations, the Jamaican government published the National Invasive Alien Species Strategy & Action Plan (NIASSAP) in 2014. Despite apparent actions to reduce the impact of some invasive species, we observed a lack of information and awareness within the environmental community during the project; this could pose challenges when a closure plan states that invasive species are to be prohibited on a site and potential challenges should be considered before initiating the revegetation phase.

5.4.1 Lack of a conclusive list of invasive species

The NIASSAP describes in detail numerous mitigation measures but does not appear to include a list of species considered invasive. Instead, the Clearing House Mechanism (CHM) maintains a database which can be accessed online. According to the National Strategy and Action Plan on Biological Diversity in Jamaica, there are over 120 species in Jamaica that are listed as invasive, however, up to May 2023 only 86 species are shown in the database. Even more confusing is the fact that the Forestry Department (an agency within the Ministry of Housing, Urban Renewal, Environment and Climate Change) maintains its own list of invasive species (totalling 114), causing uncertainty with regards to the status of some species in the country.

In addition to the absence of a conclusive list, the information on the current list is sometimes incomplete. For example, *Leucaena leucocephala* consists of three sub-species, namely *L. leucocephala* ssp. *glabrata*, *L. leucocephala* ssp. *ixtahuacana*, and *L. leucocephala* ssp. *leucocephala* of which the latter is generally considered an invasive species (Sharma et al. 2022). Neither the CHM database, nor the invasive species list of the Forestry department, mentions the subspecies that is considered invasive in Jamaica.

5.4.2 Lack of knowledge within the environmental community

Many professionals within the environmental sector in Jamaica do not seem to be aware of the invasive status of some of the plant species. An example of this was experienced during the revegetation project, where *Casuarina equisetifolia* (which is listed as invasive according to both the CHM database and the Forestry Department list) was being sold by the Forestry Department at all their nurseries in the island, encouraging the local community to plant this tree species. In addition, the production of many invasive fodder species, like *L. leucocephala* and *Megathyrsus maximus* are encouraged by several agencies within the Jamaican Ministry of Agriculture and Fisheries.

Uncertainties, knowledge gaps, errors, and disagreements amongst specialists with regards to invasive species listings are challenges that many areas in the world are struggling with (McGeoch et al. 2012; Zenetos et al. 2017; Băncilă et al. 2022). Resolving such issues are complex, but acquiring reliable data on species' distribution, educating various environmental agencies, and improving communication and cooperation between various government departments, NGO's, and private sector would be a first step to improve on the management of invasive species.

Conclusion

A recent shift within the field of invasion biology towards a more holistic approach regarding non-natives, has brought attention to their positive impacts including their potential conservational value; a possibly useful change in perspective for the mining sector that is now facing constant challenges remediating tailings. The prolific seed production, rapid growth, and overall resilience of many non-native species, especially invasives, are all well sought-after cultivation features essential to many remediation projects, particularly for mine tailings taking into account the adverse conditions that can exist for some of the waste material that plants need to grow in.

During Rio Tinto's remediation projects in Jamaica, where various conditioned bauxite residue sites have been remediated without the use of topsoil, many benefits of non-native plants (including species that became classified as invasive after the project had commenced and approved by the government regulators) were observed, and numerous species had a rapid and positive impact on biodiversity, soil quality, erosion and dust control, and showed signs of both long term continuation and resilience to adverse weather conditions.

Though native species are expected to perform equally as well under 'normal' circumstances (if not better), under the hostile conditions as observed on the Mount Rosser bauxite residue disposal site (high pH, high sodium, prolonged drought and seasonal flooding in some areas), the non-native species appear to be more advantageous in two critical categories: (1) performance (growth and survival rate) and (2) availability of planting material.

In a case where native plants are inadequate, limited, or cannot meet the closure objectives, some non-native species may form suitable alternatives based on their observed prolific reproduction, adaptability, and numerous positive impacts. However, developing criteria to assess risks of using non-native species is important moving forward. Rather than ruling out a species based on its origin, we should focus on other factors, such as harmful features of certain plants (e.g. the ability to smother newly planted seedlings) and risk of invasion, and even take into consideration some of the 'grey areas' related to invasive species. This will provide an opportunity for the mining industry to review the possibility of using non-native species on a case-by-case basis and aim for long term resilience and diversity.

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