BR01 - Evaluation of Bauxite Residue Rehabilitation Strategy: One Year Monitoring Assessment

Yuuki Miura[1], Ronaldo Pantoja[2], Adriana de Cassia Souza[3], Paschoal Cataldi[4], Daniel Arvani[5] and João Wendell Santos[6]
1. Project Engineer
2. Project Engineer
3. Project Engineer
4. Project manager
5. Engineering manager
6. Operation supervisor
Hydro Alunorte, Barcarena, Brazil
Corresponding author: yuuki.miura@hydro.com

Abstract

The Bauxite Residue Disposal Area (BRDA) of Hydro Alunorte refinery has received residue since beginning of its operation in 1995 and current total area is approximately 270ha. Annually, the refinery produces over than one million cubic meters of bauxite residue. Following global best practices, Hydro Alunorte has invested in press filtration of the residue since 2016, a novel technology ensuring safer disposal. Furthermore, the company started in 2018 the rehabilitation of BRDA to reduce dust generation, wastewater and other environmental risks usually associated with bauxite residue. BRDA Closure project was developed for Hydro Alunorte to be implemented in annual strips of rehabilitation within 15 years, including construction of experimental sites to evaluate suitable alternatives of cover layers and capping over the residue. The present work was undertaken to evaluate the success of rehabilitation conducted on eight sites of 1500 m² within Bauxite Residue Disposal Area at Alunorte – Alumínio Norte do Brasil S/A refinery. This was achieved by monitoring natural regeneration, plant mortality, wastewater quality of runoff and underdrainage by lysimeters. All sites were revegetated in April 2019 which received different covers and capping alternatives. Wastewater quality was bimonthly assessed for main metals present in bauxite residue besides pH. Plant mortality and natural regeneration was assessed semiannually by in situ plant identification. Soil samples were collected form 20 cm composite sampling and analyzed for main metals. Plant mortality were lower in treatments that received permeable caps (1A and 1B) followed by in situ remediation (3A) with gypsum and soil without capping. Natural introduction of new species was also higher in treatments with permeable caps and in situ remediation (areas 1A, 1B and 3A). More tests applying is situ remediation strategy is recommended to evaluate long term efficiency.

Keywords: Bauxite rehabilitation, Hydro Alunorte.

1. Introduction

Hydro Alunorte is one of the biggest refineries in the world and is estimated that more than 50 million meters cubic is deposited at its Bauxite Residue Disposal Area – BRDA. Since 1995 Hydro Alunorte BRDA has storage residues at BRDA and current total area is approximately 270 ha. Management and remediation of bauxite residue is considered the major challenge for the alumina industry in terms of environmental and social as aspects. Following global best practices, Hydro Alunorte has invested in press filtration of the residue since 2016, a novel technology ensuring safer disposal. Furthermore, the company started in 2018 the rehabilitation of BRDA in order to reduce dust generation, wastewater and other environmental risks usually associated with bauxite residue. BRDA Closure project was developed for Hydro Alunorte to be implemented in annual strips of rehabilitation within 15 years, including construction of experimental sites in order to evaluate suitable alternatives of cover layers and capping over the residue. The closure of BRDA has historically received installation of a cap or cover system below the soil layers for plant growth in order to isolate the underlying bauxite residue from further rainfall generating contaminated leachate. Cover system is made by high density polyethylene, which prevents rainwater infiltration to bauxite residue layers. This impermeabilization consequently avoid water moving upwards with high pH and high alkalinity reaching the roots zone [1]. Capping of bauxite residue ensures that the soil is not contaminated maintaining soil quality thereby plant growth. Some authors have affirmed that cap and cover system do not provide "walk-away" solution for bauxite residue closures, as the geochemical and physical properties remains unchanged [1]. Several work applying in situ remediation in bauxite residue has carried the last decades [2,3,4], however there is not a consensus regarding the methodology. Therefore, despite disagreement in its use, capping system is still considered the safest and fastest method for vegetation cover and environmental impacts mitigation.

To date, two main approaches are employed for tailing management: "cap and store" or "in situ remediation" At in situ remediation, amendments (organic or inorganic) are added to bauxite residue expecting changes in its key physical and chemical properties towards to natural conditions providing a substrate able to sustain vegetation growth. Currently, application of gypsum combined with organic amendments are the most usual remediation approach [5], also microbial application as bioremediation strategy was studied [2]. In both cases results has been successful decreasing pH, salinity and sodicity, decreasing bulk density and increasing aggregation. Application of *in situ* remediation in BRDA closure is only possible when amendments are highly available, low cost and easily accessible, otherwise the closure project might become more expensive than when capping system is applied [6]. In contrast, cap and storage methodology isolate the residue by high density polyethylene liners or impervious layers at the top (eg. compacted clay) followed by soil layers with drainage system at the base to collect and transport the leached. Liners avoid rainfall to reach bauxite residue minimizing the possibilities of contaminated leached (high pH, high salinity and high dissolved metals concentrations) impact surrounding areas. The result of total insulation of the residue is that the leached has contact only with soil layers generating leached within the limits of environmental legislation. Also, installation cost of rehabilitation methodology is an important factor that must be considered. Generally, capping the residue increase the cost of rehabilitation compared to in situ remediation due to costs of liners and following layers and drainage system. However, if amendments are costly due to transport or difficulties to be obtained in situ remediation may become as expensive as capping and store method.

Reduce environmental risk of bauxite residue by addressing high alkalinity and salinity of dust and leached are the major challenges of tailings closure projects. Permeable caps have been demonstrated positive effects on vegetation establishment in bauxite residue [6]. However, few works have demonstrated the effects of total and partial insulation of bauxite residue in leached and vegetation growth to date. Effects on vegetation and leached will depend on capping insulation capacity and compaction of over layers. For example, high density polyethylene liners isolate completely the bauxite residue whereas geotextile isolate partially permitting infiltration of rainfall.

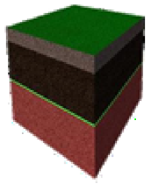
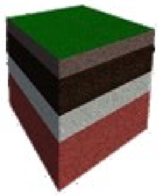
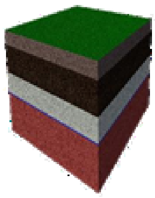
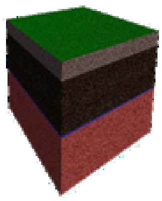
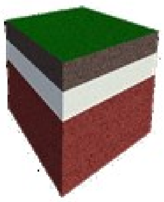
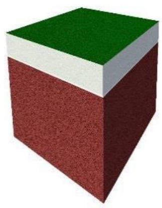
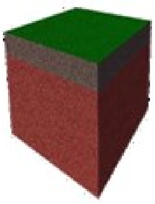
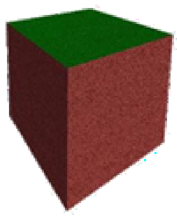
The present work was undertaken to evaluate the success of rehabilitation conducted on eight sites of 1500m² within Bauxite Residue Disposal Area at Alunorte – Alumínio Norte do Brasil S/A refinery. This was achieved by monitoring natural regeneration, plant mortality, wastewater quality of runoff and underdrainage by lysimeters. All sites were revegetated in April 2019 which received different capping alternatives and amendments. Wastewater quality was bimonthly assessed for main trace elements present in bauxite residue besides pH and Electrical Conductivity. Plant mortality and natural regeneration was assessed semiannually by in situ plant identification. Geotechnical data from piezometers were investigated bimonthly in order to assess groundwater flow for each site. The main goal of this work was to compare effects of capping alternatives and in situ remediation of bauxite residue in vegetation establishment and leached.

2. Materials and Methods

2.1 Site History and Sample Collection

Hydro Alunorte operate alumina refinery since 1995 and currently own 2 bauxite residue disposal area (DRS1 and DRS2). Due to DRS1 deposition reaching the limit, the company started its closure plan in 2019 with an estimated completion in 2035. To evaluate the best closure practice to be implemented, 8 test sites of 1500 m² each were established in 2018 receiving different treatment, cap and covers. Before capping and covering with layers the drum filter residue was covered and reshaped by filter press bauxite residue. The Figure 1 shows different methodologies applied in the test fields.

Table 1. Cap and cover alternatives applied on the test fields.

Area 1A - permeable cap		Area 1B - permeable cap	
1- Drainage geocomposite above residue 2- 60cm densified soil 3- 20 cm thick final topsoil 4- Revegetation		1- 30cm layer of sand above residue 2- 40cm of densified soil 3- 20 cm thick final topsoil 4- Revegetation	
Area 2A - impermeable cap		Area 2B - impermeable cap	
1- Liner above residue 2- 30cm thick layer of sand 3- 40cm of densified soil 4- 20cm topsoil 5- Revegetation		1- Liner above residue 2- 60cm densified soil 3- 20cm thick topsoil 4- Revegetation	
Area 3A - no cap (in situ remediation)		Area 3B - no cap (in situ remediation)	
1- Amendment with gypsum 2- 30cm of topsoil 3- Revegetation		1- Amendment with gypsum 2- Revegetation	
Area 4A - no cap (in situ remediation)		Area 4B - no cap (control)	
1- 30cm topsoil above residue 2- Revegetation		1- Revegetation directly over the residue	

After capping, sites were fertilized at the same rates with a general purpose of agricultural fertilization containing N, P, and K and seeded with a mixed species. Effluent samples were taken from collecting boxes (runoff and lyzymeters) bimonthly. Biannually, within each sampling site, three replicate pits were dug by excavator to maximum depth of 20 cm and mixed to make composite sample of soil.

2.2 Water Chemical Analysis

The pH and EC and of run-off and under drainage were measured in loco by Horiba U-50 multiparameter. The samples for analysis of metals and non-metals were acidified in nitric acid (pH < 2). The preservation of the samples for analysis of dissolved organic carbon was performed using orthophosphoric acid to obtain a final acidity of 10 % [7]. An inductively coupled plasma optical emission spectrometer (ICP-OES) with axial and radial vision was used for metals concentration analysis. (Icap 6500 Duo, Thermo Scientific, Cambridge, United Kingdom).

2.3 Soil Chemical Analysis

All samples were prepared with deionized water obtained from an osmosis and deionizer system. Nitric acid 65 % (v/v) previously purified by a distillation system (BSB 939-IR, Berghof), hydrochloric acid, hydrofluoric acid and boric acid were used in the preparation of soil samples. Barium chloride solution 10 % (m/v) was used to extract boron from soil samples. The soil samples were dried in an oven at 105 ºC for 3 days. After these 3 days, the samples were ground and stored in bottles in a desiccator. A mass of approximately 0.25 g of each soil sample in digestion flasks and then added 4 ml of 65 % HNO3 (v/v), 2.5 ml of 37 % HCl (v/v) and 1.5 mL of 40 % HF (v/v). Aluminum (Al), calcium (Ca), iron (Fe), phosphorus (P), magnesium (Mg), potassium (K), sodium (Na), were determined in soil samples by ICP OES and mercury by DMA.

2.4 Plant Mortality and Natural Regeneration

Plant mortality and natural regeneration was surveyed biannually by in loco evaluation. Plant mortality is given by percentage by comparing the original number of plants to in loco actual number of each survey. Natural regeneration is measured by in loco investigation comparing the original species with the new species found in each treatment.

3. Results

3.1 pH Results of Runoff and Under Drainage

There was significant interaction between cap and cover application for pH (Figure 1). The pH of run-off is generally higher in those areas without capping except area 1B that had pH higher than legislation limit for discharge to the nature (pH 9) from January 2019 to May 2020. Areas 3B and 4B (without soil cover) as expected had pH above the limit varying between 9 and 10,5. Areas that received soil cover maintained the pH < 9 during monitoring period. For under drainage effluent (Figure 2) is expected higher pH in areas without cap or impermeable cap due to possibility of interaction of infiltrated rainfall with bauxite residue and consequently increasing the pH of effluent. Areas 1A and 1B (permeable cap) had the pH >9 during monitoring period varying between 9,5 and 11,5. Areas 2A and 2B (impermeable cap) despite lower pH than areas 1A and B still presented results above legislation limit but tendency of reduction at area 2A. Area 3A presented pH between 9 and 10,5 whereas 4A varied between 8 and 9,5.

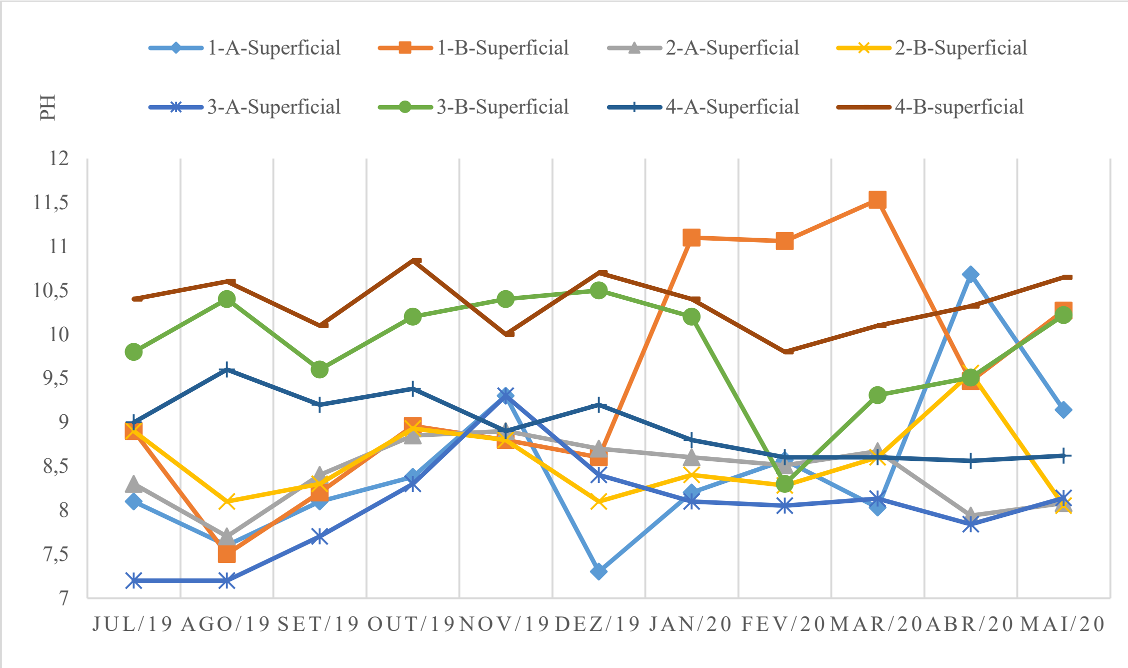


Figure 1. pH of run-off effluent from 8 sites within DRS1 - bauxite residue storage area at Hydro Alunorte.

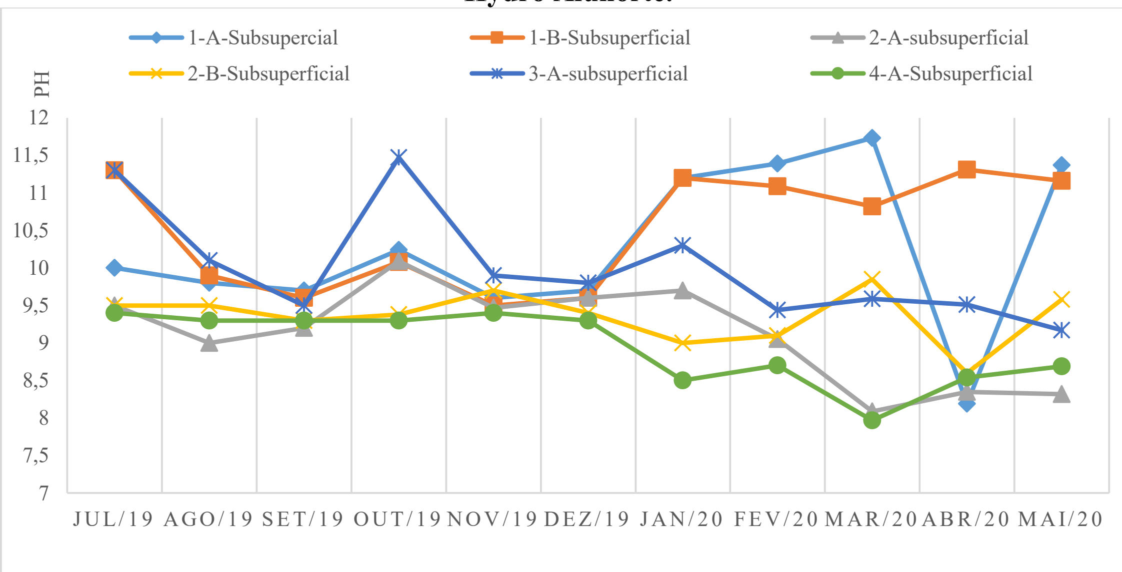


Figure 2. pH of under drainage effluent from 8 sites within DRS1 - bauxite residue storage area at Hydro Alunorte.

3.2 Effluent Chemical Analysis

Aluminum (Al) and Sodium (Na) concentration of runoff in areas 3B (in situ remediation with gypsum) and 4B (control) presented the highest results from all treatments (Figure 3). This was expected since the rainfall interact directly with bauxite residue and consequently being contaminated. Whereas areas that received soil cover had low Al and Na concentration, with slight variation along the period that might be the influence of dust from unrehabilitated areas.

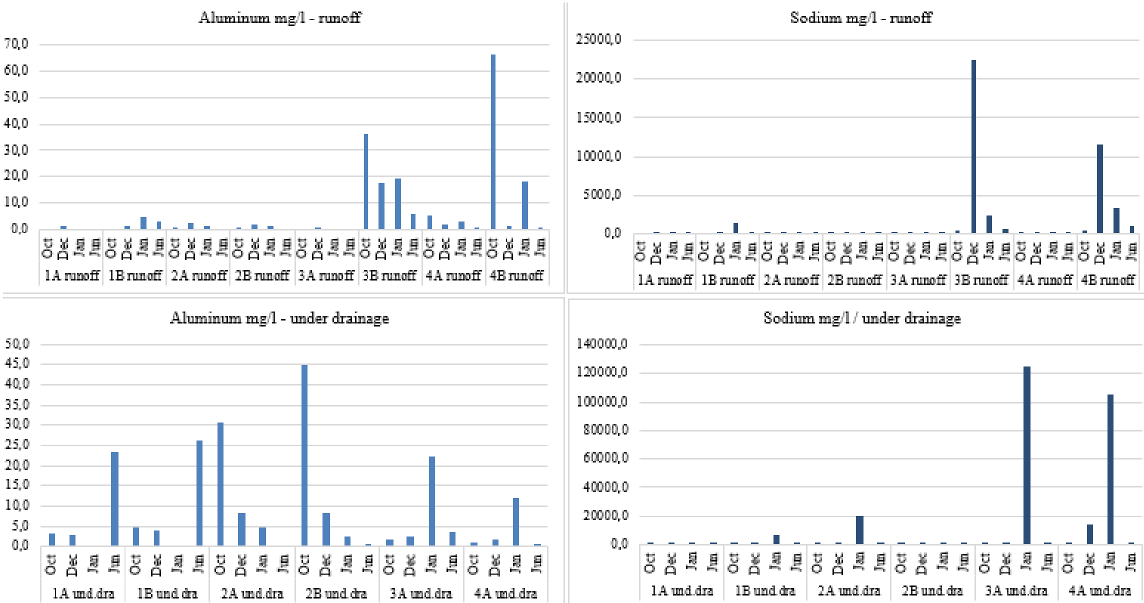


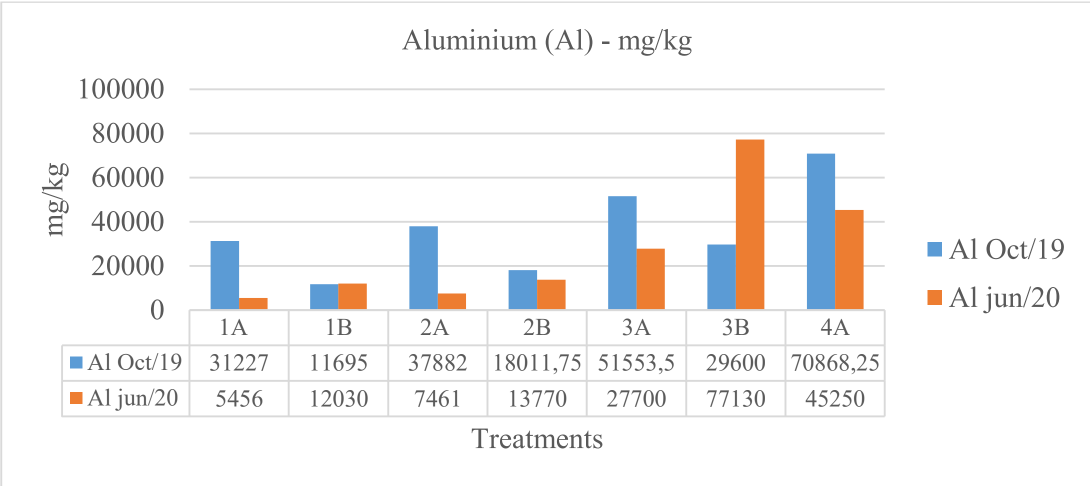
Figure 3. Aluminum (Al) and Sodium (Na) concentration of runoff and underdrainage effluent from 8 sites within DRS1 - bauxite residue storage area at Hydro Alunorte.

Aluminum (Al) had heterogeneous results along the period and between the treatments. Despite the impermeable cap over bauxite residue and subsequent layers of sand and different types of soils, areas 2A and 2B present unexpected high concentration of Al in October and December of 2019 in comparison with other treatments. This might be explained by the natural concentration of Aluminum in Amazon soils. Another supposition is contamination of underdrainage layer by bauxite residue during construction phase.

In January Na presented the highest concentration for all treatments due to higher precipitation rates during this period, consequently more infiltration and reaction with bauxite residue. In this period area 1B presented higher Na concentration (6339 mg\l) than 1A (1585,8 mg\l) showing that sand cap might be less efficient than drainage geocomposite against effluent capillarity raise. Area 2A (impermeable cap) showed unexpected result in January with Na concentration reaching 20025mg\l whereas 2B (impermeable cap) reached 927,1 mg\l.

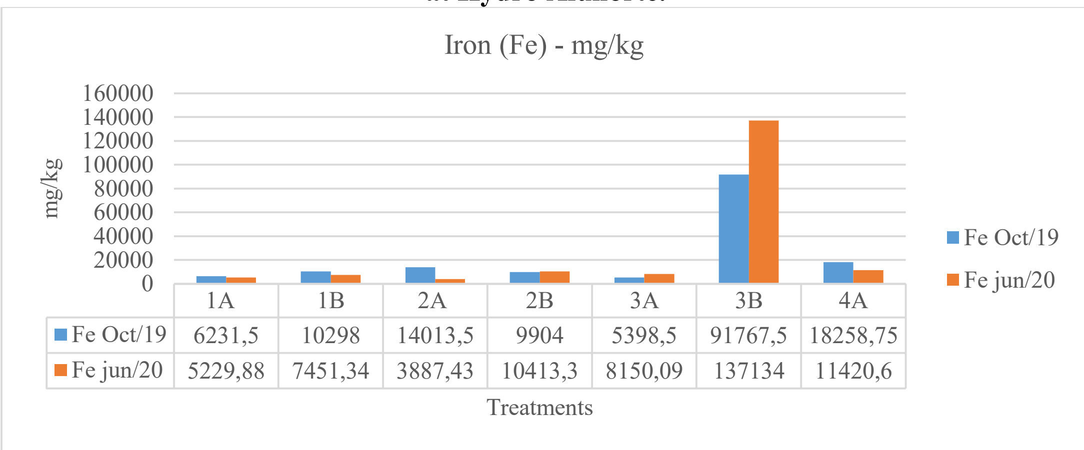
3.3 Soil Chemical Analysis

Metal concentration of Aluminum (Al), Iron (Fe) and Sodium (Na) were higher at area 3B (in situ remediation) which did not receive soil cover but only gypsum as amendment. Despite soil cover in the areas 1A, 1B, 2A, 2B, 3A and 4A Al and Fe concentration was high due to natural characteristics of Amazon soil. Na concentration were higher in October 2019 but there was a slight reduction in Jun 2020 in 1A, 1B, 2A, 2B and 3A.



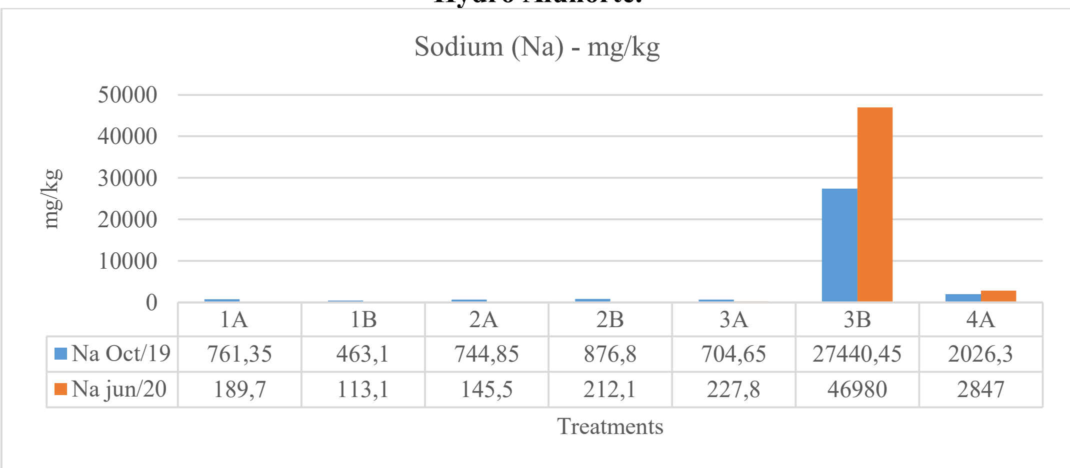
	1A	1B	2A	2B	3A	3B	4A
Al Oct/19	31227	11695	37882	18011,75	51553,5	29600	70868,25
Al jun/20	5456	12030	7461	13770	27700	77130	45250

Figure 4. Aluminum concentration from 8 sites within DRS1 - bauxite residue storage area at Hydro Alunorte.



	1A	1B	2A	2B	3A	3B	4A
Fe Oct/19	6231,5	10298	14013,5	9904	5398,5	91767,5	18258,75
Fe jun/20	5229,88	7451,34	3887,43	10413,3	8150,09	137134	11420,6

Figure 5. Iron concentration from 6 sites within DRS1 - bauxite residue storage area at Hydro Alunorte.



	1A	1B	2A	2B	3A	3B	4A
Na Oct/19	761,35	463,1	744,85	876,8	704,65	27440,45	2026,3
Na jun/20	189,7	113,1	145,5	212,1	227,8	46980	2847

Figure 6. Iron concentration from 6 sites within DRS1 - bauxite residue storage area at Hydro Alunorte.

3.4 Revegetation Assessment

3.4.1 Plant Mortality

After 18 months since seeding the results of plant mortality is presented in figure 4. In treatments with permeable caps (1A and 1B) the plant mortality was 12 % and 19,2 % respectively. For treatments with impermeable caps (2A and 2B) the mortality was 25,9 % and 31,9 %. For treatments that in situ remediation was applied 3A showed the lowest mortality (25,4 %) followed by 4A (71,1 %), 3B (79,9 %) and finally the 4B (control) with 100% of mortality. Impossibility of water infiltration and consequently water logging seems to increase plant mortality in 2A and 2B (impermeable cap) compared to 1A and 1B (permeable cap) and 3A (in situ remediation). Also, soil cover was the main factor for plant growth success since all treatments with soil presented the lowest mortality rates. Despite gypsum had been universally applied for bauxite residue remediation, the utilization of this material without soil did not have desirable effect in plant development. Also, area 4A that received topsoil as amendment did not present satisfactory result showing that the best option for in situ remediation in this study was the mix of amendment by soil and gypsum (3A).

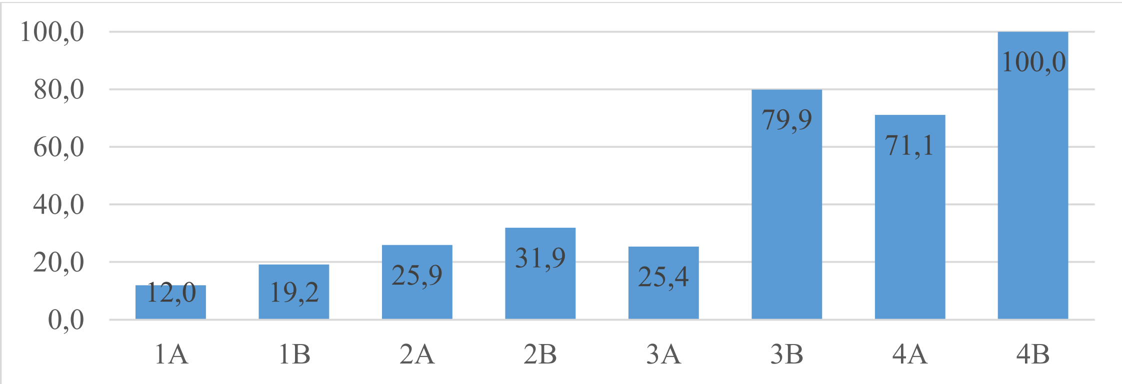


Figure 7. Plant mortality after 18 months after seeding from 8 treatments within DRS1.

3.4.2 Natural Regeneration

Area 1B and 3A presented the highest number of species naturally introduced in the area (31) after almost 12 months, followed by 1A (28), 2A (26), 4A (25) and 3B (12) (Figure 8). Area 4B (control) was not assessed due 100 % of plant mortality as shown previously. From the treatments that received cap layer 1A and 1B (permeable cap) had higher number of new species showing that water logging also may affect establishment of natural species. Area 3B which did not receive cover of topsoil presented the lowest number of new species following similar results of plant mortality.

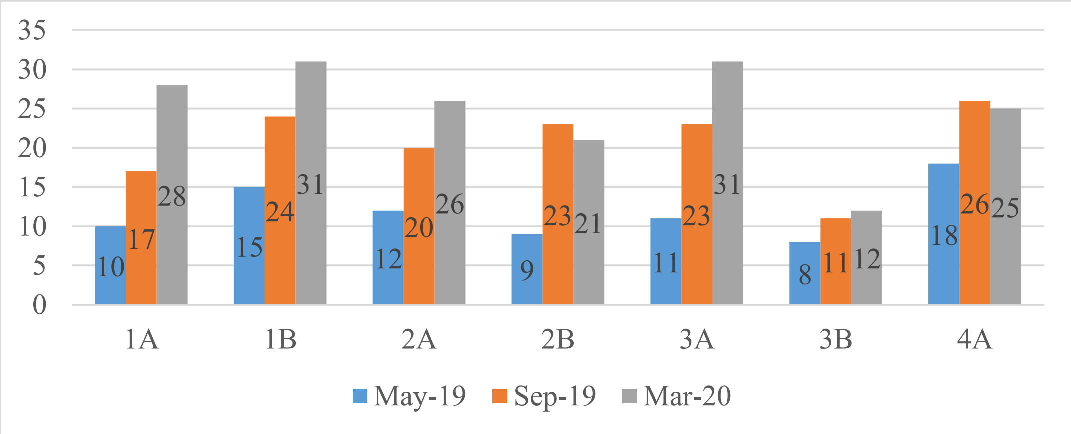


Figure 8. Number of new species introduced naturally in 8 treatments within DRS1 disposal area. Area 4B did not have any introduction of new species.

4. Conclusions

The current work was undertaken in 8 treatments with 1500 m², during 12 months of monitoring. It is important to note that this work does not provide results with statistical analysis, therefore there are no replication that support conclusions and recommendations. Nonetheless, the results seen on the field give us important inputs for the future rehabilitation which are listed below:

- Impermeable cap affected negatively plant development compared to permeable cap;
- Area 3A (in situ remediation) had better plant development compared to 2A and 2B (impermeable cap);
- Concentration of Sodium (Na), Aluminum (Al) and Iron (Fe) seems to affect plant development and natural regeneration in areas 3B and 4A;
- Layers permeability may have affected metal concentration in underdrainage effluent.

To confirm these results, plant development at the first rehabilitation strip, where 7ha was rehabilitated applying impermeable cap (same as area 2B), will be followed up. If the low plant development is confirmed permeable cap may be applied in following strips of rehabilitation. In addition, one more test field of 1500 m² will be added to investigate in situ remediation with different amendments materials available in northern of Brazil.

5. References

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