REVEGETATION OF ACID FORMING MINE SPOILS IN PARACATU, MINAS GERAIS STATE, BRAZIL[1]

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Abstract: Paracatu is located in northwest Minas Gerais State, 230 kilometers from Brasília, the capital of Brazil, and for the last two centuries has been an important gold mining site. With more of 600 ha of acid-sulfate soils across the open cut mine to be revegetated, the company is working to develop a method to reliably establish sustainable vegetation and minimize acid drainage. With this goal, we established a field experiment to evaluate five soil placement combinations to isolate (saddle) and/or cover the acid substrate. We also evaluated five plant species and three combinations to revegetate the materials. The five cover treatments were composed of three layers to: 1) isolate/saddle the substrate; 2) break capillarity and, 3) form a suitable surface material for plant growth. Ore (from mining zone B1) or clay was used as the saddle layer and sand, lime gravel, and sand plus oxalic acid were tested as capillary barriers. Then KCl and NaCl were also added to induce jarosite formation (geochemical barrier) to reduce availability of Fe and As in the drainage. As a cover layer, we tested B1 and local B horizon clay. Each (3) experimental block was comprised of five plots (to test the layers materials) with eight split sub-plots to evaluate the species and combinations. Ten months after establishment, we took samples of the layers to evaluate density and porosity, and the revegetation species were sown. Preliminary results showed that the saddle layer with clay resulted in higher density/less porosity. Non-compacted clay, when used to form the third layer, had higher water retention than B1 ore. This characteristic is very important to reduce water movement into underlying acid-sulfate materials. Among the evaluated species, *Crotalaria juncea* performed best followed by *Melinis minutiflora*. For most tested plant species and mixtures, the use of clay as the first and third layer coupled with sand plus KCl and NaCl as the capillary barrier resulted in optimal biomass production.

Additional Key words: Acid mine drainage, gold mine reclamation, acid sulfate soils.

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Introduction

Brazil, mainly the State of Minas Gerais, has many different mineral resources that represent an important contribution to the national economy. Some of these ores are associated with sulphides, which through post-disturbance oxidation can generate acidity and to promote the solubilization of metals and toxic metalloids. This acid mine drainage (AMD) is then carried with drainage water to local streams, which represents the dominant impact of mining in many watersheds. Once the oxidation process is initiated, production of acid water occurs over the active lifetime of the mine and beyond unless appropriate remedial practices are applied. Several remedial practices are common in use over the world (e.g. use of alkaline materials and capillary barriers) and many other new approaches are under study. One practice that promised good effectiveness with respect to limiting arsenic (As) mobilization is the induction of formation of a reactive geochemical barrier. In theory, barrier geochemistry consists of the induction, through the addition of chemical compounds and additives, of new minerals from the reaction products of sulphide oxidation. In the case of the arsenopyrite, the main minerals formed in this barrier are jarosite and the natrojarosite that significantly decrease As mobility to leaching and runoff waters (Assis, 2006).

The formation of these minerals can mitigate AMD impacts over both the short and medium term because these minerals are stable at pH values as high as 4.0, becoming unstable only when pH and redox potentials reach higher values. Possibly, the primary elemental components of this mineral group convert into stable iron oxides, possibly maintaining the immobilized pollutants (and the mitigation effects) for longer periods of time. However the dynamics of these processes are not known and determining whether or not this long term immobilization of As and other problem compounds really occurs will demand further studies.

One AMD mitigation practice that does seem to be effective in reducing the process of formation of acid drainage is the use of evapotranspiration layers that reduce the amount of water that arrives to the sulphidic material. These layers consist of different materials, usually sand, with different sizes, layered above the acid forming material, which generate better conditions for evapotranspiration, reducing the leaching water that reaches the sulphidic materials. For this method to work, however, it is essential for a viable plant community to be present.

The Environmental Geochemistry and Reclamation of Degraded Areas group of the Soils Department, Federal University of Viçosa, has been executing research on materials from different mining sites since the beginning of the 1990's. Different projects have focused on tailings, spoils and overburden of coal, Au and Zn mining wastes. These projects have involved mining companies from the States of Rio Grande do Sul, Santa Catarina, Minas Gerais and Pará. In one recent project, the evaluation of different procedures for the mitigation of acid drainage in constructed column/lysimeters indicated that the application of K and Na into the cover layer over sulphidic substratum promoted jarosite and natrojarosite formation. This was also shown to be an important mechanism for the reduction of Fe, S and As concentrations in the lysimeter leachates (Assis, 2006).

Paracatu is located in the northwest part of Minas Gerais State, 230 kilometers from Brasília, the capital of Brazil, and for the last two centuries has been an important gold mining site. Gold and sulphide mineralization is localized within a 120 -140 meter thick high strain zone that dips gently to the SW and is traceable for over 6 km along a NE-SW trend, and is more than 3 km in width. The nominal processing plant throughput is 1.5 million tons per month or 18 million tons per year, considering the present ore hardness. With more of 600 ha of acid-sulfate spoil dominated open-cut mine to be revegetated, the company is working to develop a method to reliably establish sustainable vegetation and minimize acid drainage. With this goal, we established a field experiment to evaluate five soil placement combinations to isolate (saddle) and/or cover the acid substrate and five plant species and three combinations of these species to revegetate these acid forming spoils.

Material and Methods

The field experiment was established in rock spoil of a gold-mined area in Paracatu-MG. According to Köppen's climatic classification, Paracatu's Region belongs to the type Aw – climate Savannah humid tropical, with dry winter and rainy summer. The annual average temperature is 22.6°C, with average colder months at 8°C and the average hotter months are 29.1°C. The annual average precipitation is 1,400 mm, but in drier months, rainfall drops below 60 mm.

The dominant substrate on-site is composed of crushed phyllites and is less oxidized and is designated B2. This material contains around 10 g kg^{-1} of sulfidic minerals. The area of the experiment (9,000 m^2) was divided into three blocks, each one 75 m in width and 40 m long. The experiment was established in two stages: the first testing treatments for covering the substratum (Table 1 and Fig. 1) and the second (15 months later) evaluating the growth of different vegetation species. Each block was comprised of plots 15 m x 40 m, and each plot subdivided in eight subplots of 75 m^2 each (5 m x 15 m). Therefore, each (3) experimental block was comprised of five plots (to test the layered materials) with eight split sub-plots to evaluate the species and combinations (Table 2).

Table 1. Materials used to form different layers in the field experiment in Paracatu-MG, Brazil.

Treatment	**Layers**		
	Saddle	**Break the capillarity**	**Cover**
1	B1	Sand	B1†
2	B1	Limestone gravel‡	Clay + B1
3	B1	Sand + Org. Ac.ξ	Clay + B1
4	Clay	Sand + Org. Ac. + GB§	Clay
5	B1	Sand + Org. Ac.	Clay

‡ 2-4 cm diameter.
ξ Organic acid (oxalic acid – 1.67 g kg^{-1} of sand) to promote organic saddle (Ribeiro Jr., et al. 2002).
§ Geochemical barrier induced by application of NaCl + KCl (2 % w/w) and neoformation of jarosite and, or natrojarosite.
† Low sulphide content ore.

Table 2. Data of the chemical analyses of the used materials.

Material	pH H_2O	Total As[1/]	As[2/]	P[3/]	K[3/]	Ca[4/]	Mg[4/]	Al[4/]	H+Al[5/]
		mg/dm^3				cmolc/dm^3			
Oxisol Bo horizon	4.72	15.6	0.0	1.8	25	0.37	0.60	1.20	3.30
B1	4.18	2,418.0	26.9	4.6	9	0.07	0.06	0.24	0.40

[1/] Digestion saw humid (Huang et al., 1988)
[2/] Extractable in Mehlich III
[3/] Extractable in Mehlich I
[4/] Extractable in KCl 1 mol/L
[5/] CEC for pH 7 extracted with calcium acetate 1 mol/L

The main treatments were composed of combinations of three layers to: 1) isolate/saddle the substrate (0.3 m); 2) break capillarity (0.1 m) and, 3) cover and form a suitable material for plant growth (0.5 m). Ore (from mining zone B1) or clay (local Oxisol B horizon) was used as the saddle layer and sand, limestone gravel and sand plus oxalic acid were tested as capillary barriers. Potassium chloride and NaCl were also added to induce jarosite formation (geochemical barrier-GB) to reduce availability of Fe and As in the drainage. As a cover layer, we tested B1 and clay (50 % clay + 50 % B1). The organic acid promotes saddling, preventing upward water migration. The data on the chemical and physical analyses of the materials used (clay, ore) are presented in Tables 2 and 3.

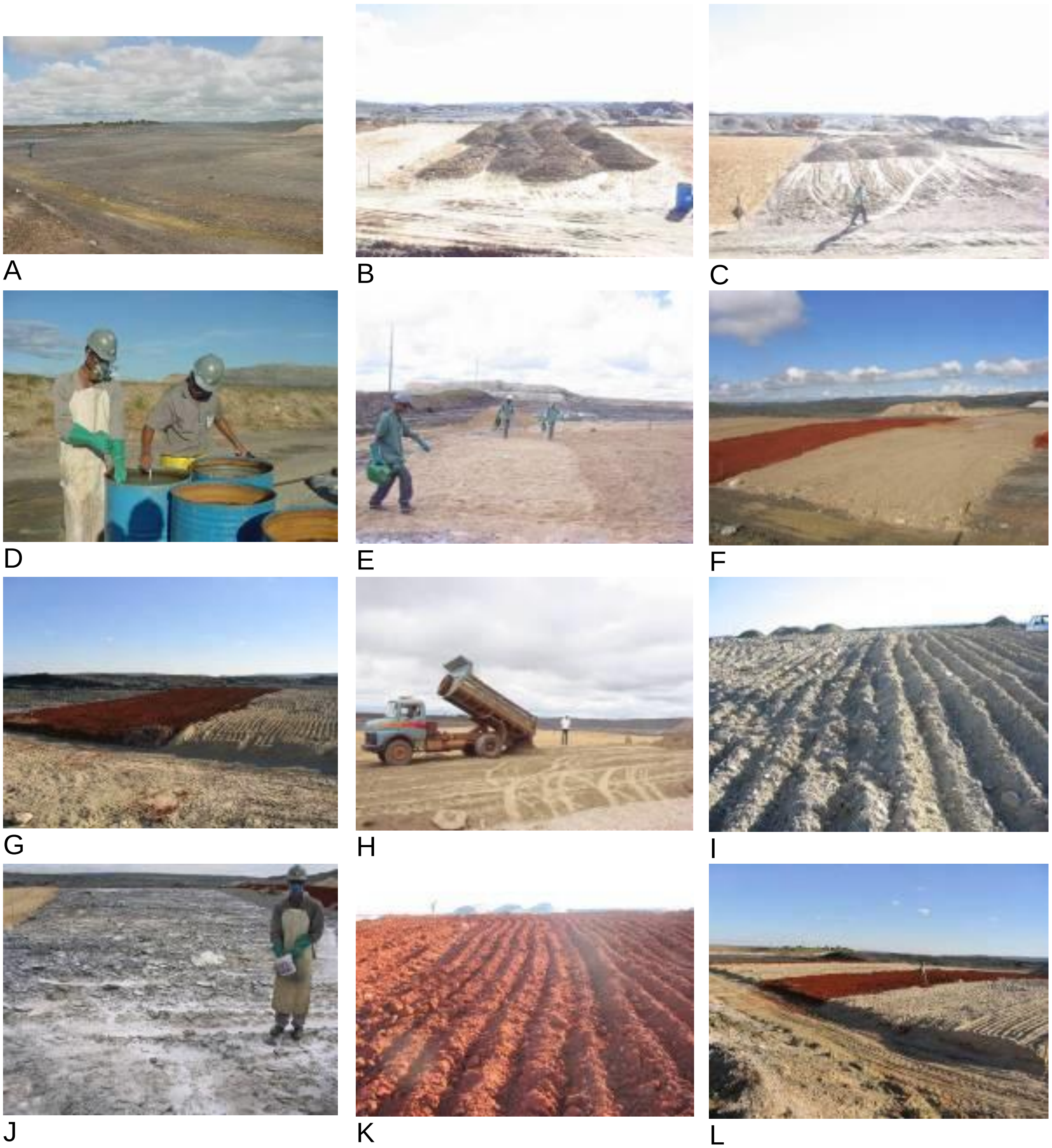

Figure 1. Views of establishing the first stage of the experiment: A. Overview of the site; B. Distribution of sand; C. Distribution of limestone gravel; D. Preparing the oxalic acid solution; E. Application of oxalic acid; F. Saddle layers with compacted clay and B1; G. Cover layers with clay and B1; H. Application of B1 over compacted B1; I. B1 as cover layer; J. Application of NaCl and KCl as geochemical barrier;. K. Clay as a cover layer; L. Overview of one block after the procedures are completed.

Ten months after establishment, we took samples of the layers to evaluate bulk and particle densities and porosity (obtained by the relation of bulk density with particle density). The samples were taken across transects of all treatments and blocks using a standard ring coring sampler. Additional samples were also taken to evaluate water holding capacity (between – 33 KPa and -1,500 KPa).

Before (15 days) the revegetation species were sown, all of treatments received a manual application of ground limestone (2.0 t ha^{-1}). All plots were fertilized by application into the planting row of N-P-K (6-30-6) fertilizer at 500 kg ha^{-1}. The evaluated species, the applied amounts, and the cultural value of the species utilized are presented in Table 4. Besides the five individual species, we also evaluated three mixtures of species with and without fat grass, in the presence and absence of mulching.

Table 3. Data of physical analyses of the materials utilized.

Material	Coarse sand	Fine sand	Silt	Clay	Soil density
	%				g/cm^3
Oxisol Bo horizon	1	2	38	59	1.18
B1	18	7	73	2	-

Table 4. Species evaluated in the experiment.

Species	**Family**	**Amount of seed**
		kg ha^{-1}
1. Avena strigosa (black oats)	Leguminous	50
2. Melinis minutiflora (fat grass)	Leguminous	50
3. Mucuna pruriens (velvetbean)	Leguminous	50
4. Raphanus sativus (turnip)	Leguminous	30
5. Crotalária juncea (crotalaria)	Leguminous	50
6. Mixture† with fat grass and mulching		100
7. Mixture with fat grass without mulching		100
8. Mixture without fat grass and mulching		100

† Mixture: crotalaria, black oats, velvet bean and turnip (1:1:1:1).

Five months after planting shoot biomass of each subplot was sampled with a 0.5 m^2 quadrat thrown at random, five times. Every existent plant inside the quadrat was cut close to the substratum and placed into paper bags for determination of dry weight.

Results and discussion

Characterization of the layers

Despite the fact that our data set contained certain variability, statistical analysis showed a significant effect for soil density as a function of treatment, particularly for the cover layer (CL) and the saddle layer (SL). In CL, the clay produced bulk densities significantly lower than B1 and the mixture of B1+clay (Fig. 2). This same result was seen for SL treatments: inclusion of clay produced lower values of bulk density (Fig. 3). The values of particle density didn't differ across treatments.

As expected, soil porosity varied between the materials and treatments. In spite of the clay's ability to produce lower value of bulk density, the saddle layer with this material produced a large porosity value (treatment 4). In other words, the ore B1 produced higher bulk density, and when compacted, it produced smaller porosity. This behavior of the clay was also verified for the covering layer (Fig. 4). The value of total porosity cannot be interpreted as being critical, because in terms of downward water movement, the larger macropores have great importance, while in the covering layers; the greater presence of micropores generates larger holding water capacity. These combined porosity related factors have great importance in relation to drainage and relative water availability for the vegetation.

The determination of plant available water-holding capacity for the materials used as cover and saddle layers indicated that the largest capacity for retention of water was in the clay derived from material B1 (Table 5). It is interesting to note that through compaction of B1 and its clay, it didn't appear to alter that capacity, indicating that the overall structure of micropores in the materials was not altered. In case of the future studies to confirm this tendency, the application of the compaction process to the saddle the layer should be reviewed.

The water-holding capacity of the materials used to saddle and cover the substratum are of great importance for the reduction of the drainage, because these layers could act as evapotranspiration layers. In other words, as the material increases along with its thickness, larger amounts of water would be held in the pores of the material, preventing it from leaching to the substratum, and subsequently limiting its promotion of oxidation of sulfide minerals and metals solubilization.

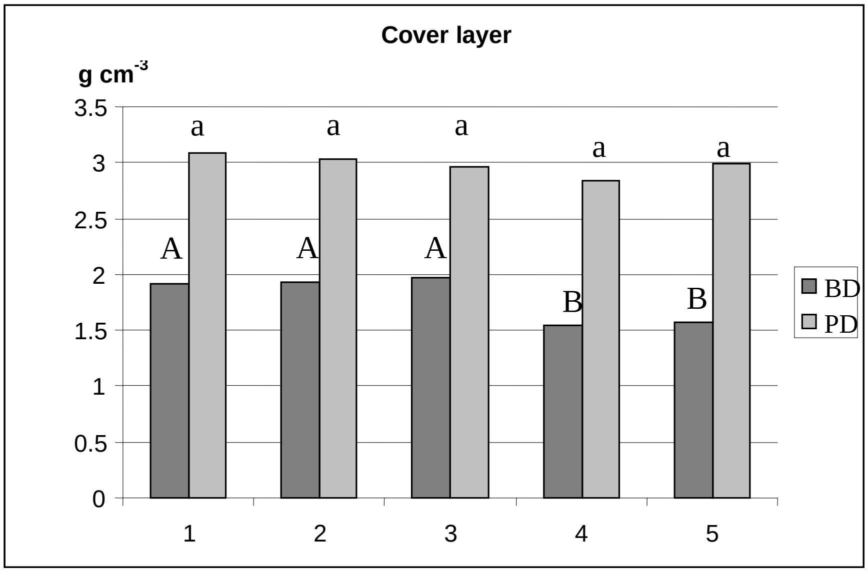

Figure 2. Values of Bulk density (BD) and particle density (PD) of the cover layers samples took from the different treatments. Densities with different letters are different at significance level < 0.05. 1= B1; 2= clay + B1; 3 = clay + B1; 4 = clay; 5 = clay.

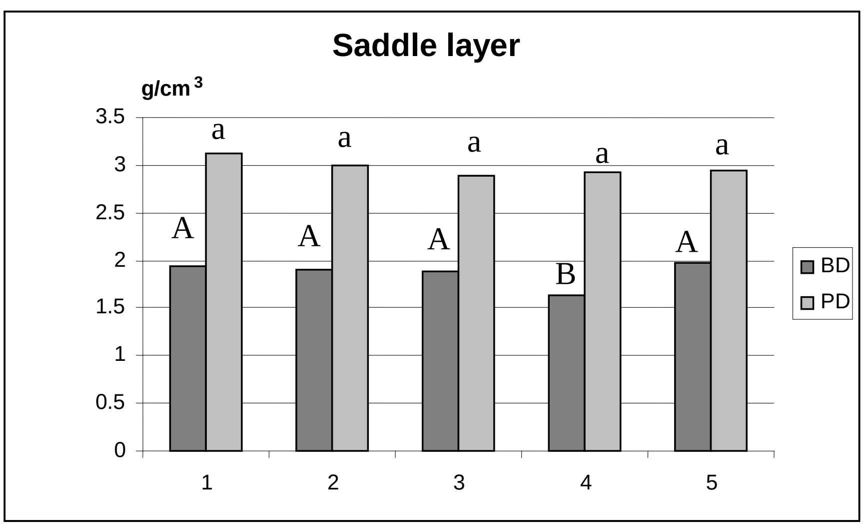

Figure 3. Average values of bulk (BD) and particle density (PD) of the saddle layers samples by treatment. Densities with different letters are different at p $\leq$ 0.05. 1= B1; 2= clay + B1; 3 = clay + B1; 4 = clay; 5 = clay.

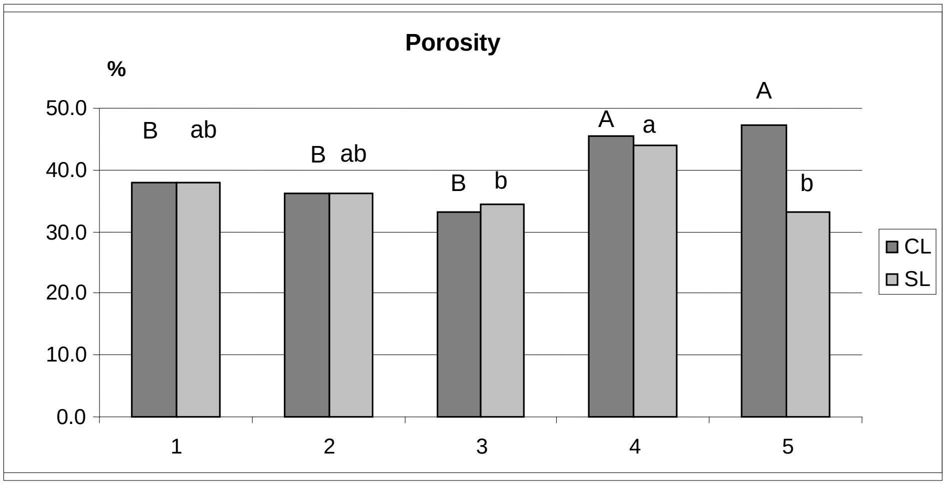

Figure 4. Average values of percentage of pores of the samples from the covering (CL) and saddle (SL) layers of the different treatments. Densities with different letters are different at p ≤ 0.05. 1= B1; 2= clay + B1; 3 = clay + B1; 4 = clay; 5 = clay.

Table 5. Average values of mass soil water content at -33 kpa and -1,500 kpa observed for the samples from B1 and clay used to compose the cover (CL) and saddle (CS) layers of the different treatments.

Treatment	**Layer**	**- 33 kpa**	**- 1,500 kpa**
		------- kg kg^{-1} --------	
1	CL-B1	0.331	0.037
1	SL-B1	0.347	0.036
2	CL-B1	0.328	0.037
2	SL-B1	0.326	0.035
3	CL-B1	0.335	0.036
3	SL-B1	0.344	0.036
4	CL-clay	0.311	0.194
4	SL-clay	0.301	0.192
5	CL-clay	0.298	0.206
5	SL-B1	0.333	0.027

Plant Growth Effects

In general terms, all of the planted species tolerated the substratum conditions and climate, remaining in good condition after five months (Fig. 5). Independent of the cover treatment, crotalaria showed the best potential to be used in the revegetation program for the substratum due to higher levels shoot biomass observed. Considering the lack of organic matter of the materials used as cover layer, it is very important to evaluate the biomass production, since it has a direct influence over carbon incorporation into substratum. This species produced, on average across all treatments, about 5.53 Mg ha^{-1} while the mixture of species with fat grass and mulching (Mix. 1) produced 3.90 Mg ha^{-1}, and the fat grass alone produced 3.79 Mg ha^{-1} (Table 6). Crotalaria is a resistant species that represents good potential for revegetation of highly sulfidic substrata due its natural occurrence on such materials as observed in earlier surveys in Paracatu (Neri et al., 2004). Another important attribute of crotalaria is it's As accumulation capacity that allows this species to be used in phytoremediation programs (Melo, 2006).

Among the evaluated species, the turnip produced the lowest biomass production and Mixture 3 (without fat grass and mulching) produced the lowest shoot biomass accumulation (Table 6). This latter result reinforces the importance of using fat grass due its high production of biomass and tolerance to adverse soil and climatic conditions.

Considering the moderate levels of shoot biomass produced among the different species and mixes as a function of the different covers system (treatments), it was clear that cover treatments 4 and 5 provided more favorable conditions to plants growth (Fig. 6). These treatments both contained lay as a covering layer. As the saddle layer, treatment 4 had clay and treatment 5 used the B1 ore.

The use of B1 as a saddle and cover layer material showed that it produces less favorable conditions for plant growth relative to the use of clay. The cover layer with clay used in treatments 4 and 5 probably resulted in more water availability to the plants, due to its higher water-holding capacity (Table 5) and lower bulk density (Fig. 2). This result also corroborates results obtained in a previous experiment (Ribeiro Jr, 2002 and Assis, 2006).

Comparing the average biomass production of all species against mixtures one and two, we conclude that the use of mulching per se did not produce higher plant growth, suggesting that this procedure may be unnecessary relative to its costs.

Table 6. Average values of dry biomass of evaluated species and mixtures of them obtained for each treatment.

Treat.	Species							
	Oats	Fat grass	Velvetbean	Turnip	Crotalaria	Mix. 1*	Mix. 2	Mix. 3
	-- Mg ha^{-1} --							
1	0.26	0.63	0.47	0.21	0.62	0.95	1.47	0.99
2	1.69	2.35	4.11	1.17	3.16	2.76	1.90	1.92
3	1.96	1.65	1.05	1.41	3.52	3.74	2.08	1.64
4	3.58	9.16	4.30	3.09	9.97	5.46	5.51	4.79
5	4.22	5.14	6.62	3.93	10.38	6.58	5.79	2.99
Average	2.34	3.79	3.31	1.96	5.53	3.90	3.35	2.47

Figure 5. Overview of the experiment five months after planting.

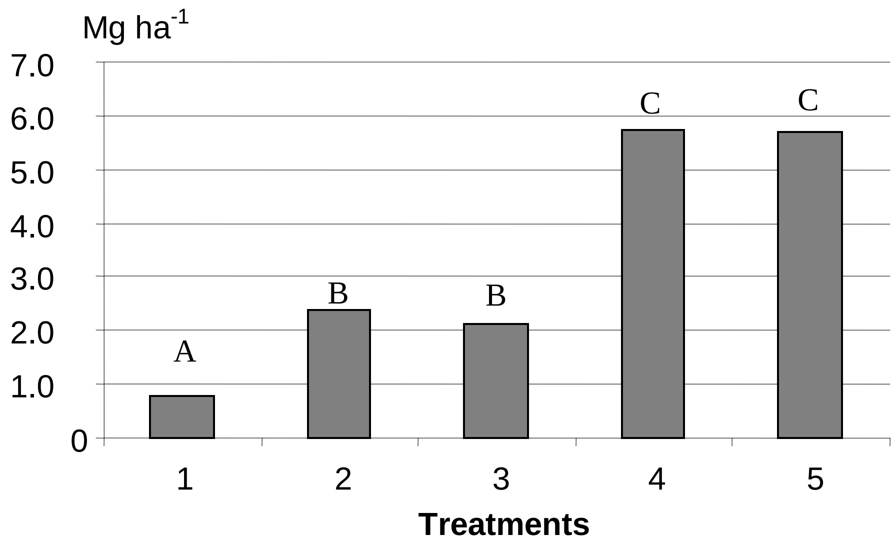

Figure 6. Average values of dry shoot biomass of all species for the different treatments evaluated. Values with different letters are different at $p \leq 0.05$.

Conclusions

The preliminary results obtained with this experiment suggest that the use of clay as a cover layer promoted better conditions for plant growth. Conclusions about the efficiency of the materials used as saddle/isolation layer to break capillarity could not be obtained without full characterization of metals concentration in shoot biomass and more time of cultivation. Among the evaluated species, crotalaria showed the highest yield potential, and the use of fat grass is important to when mixture of species will be used. The use of mulching may be unnecessary due its costs and low response. A longer-term experiment probably will produce more conclusive results.

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