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CULTIVATION OF XARAÉS GRASS IRRIGATED WITH IRON MINING TAILINGS

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KEYWORDS

degraded areas, water deficit, pasture irrigation, root system.

ABSTRACT

The collapse of the *Fundão* dam in Brazil caused one of the biggest environmental disasters. One of the challenges was how to manage the tailings so that affected areas could be reused. This study aimed to verify whether applying different irrigation depths to Xaraés grass grown with iron mining tailings would affect grass shoot and root dry masses. The experiment was set up in a randomized design with five irrigation depths (40%, 60%, 80%, 100%, and 120% of crop evapotranspiration) and two additional treatments (grass grown in tailings with soil conditioner, and grass grown in natural soil), each with three repetitions. The grass was cut four times, and the shoot dry mass was evaluated after each cut, while the root dry mass was evaluated at the end of the experiment. Our results showed that irrigation depths had a positive linear effect on shoot dry mass and an exponentially increasing effect on root dry mass, with the highest averages in the treatment applying 120% of crop evapotranspiration. This study showed that even in adverse conditions, Xaraés grass was able to grow and develop well.

INTRODUCTION

The mining industry in Brazil has a long history dating back to colonial times. The exploration of precious metals by bandeirantes shaped the occupation of the inland regions of Brazil and led to the discovery of gold in Minas Gerais (ANM, 2023). The Quadrilátero Ferrífero region (Belo Horizonte, Itabira, and Congonhas to Ouro Preto) is one of the largest mineral provinces globally and a major iron mining area in Brazil (Teixeira et al., 2021, Ribeiro et al., 2022).

Mining, however, has negative impacts, including a large number of tailings stored in containment dams (Andrade et al., 2016). In 2015, the Fundão Dam collapse in Bento Rodrigues, Mariana, MG was considered one of the biggest environmental disasters in mining, releasing 50 million m³ of tailings (Gomes et al., 2017). Tailings have physical, chemical, and structural properties different from the soil, affecting plant development during revegetation (Barros et al., 2018).

Grasses are used to recover degraded areas because of their high root density, which can improve soil physical properties like aggregate stability, penetration resistance, and reduced compaction, even in degraded mining areas (Stumpf et al., 2017). Roots of plants contribute organic matter to the subsurface soil layers through dead root cells and root exudates, which are carbon sources for decomposing microorganisms, promoting nutrient mineralization and soil structure improvement (Baumert et al., 2018).

Organic matter causes changes that favor aeration and water retention in soil, essential elements for root development, and the establishment of microorganisms processing this material (Krzyzanski et al., 2018).

This study aimed to evaluate the effect of different irrigation depths on the shoot and root yield of Xaraés grass pasture cultivated in mining tailings.

MATERIAL AND METHODS

Experiment location and waste collection

The experiment was conducted in a lysimeter station with a total area of 126 m² (18 x 7 m). It is located at the Irrigation Experimental Area of the Department of

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Agricultural Engineering (DEA) at the Federal University of Viçosa (UFV) in Viçosa, Minas Gerais. The geographic coordinates are 20º 46' 08" S latitude, 42º 52' 44" W longitude, and an altitude of 675 meters.

The iron mining tailings were obtained in partnership with the Renova Foundation, at the Germano Dam, in the municipality of Mariana – MG. A total of 30,000 kg of tailings were collected, which were used to fill 18 drainage lysimeters with dimensions of 1.40 m in length, 1.00 m in width, and 0.90 m in depth. The lower 0.15 m of the lysimeters was filled with gravel and sand, followed by 0.65 m of tailings. The geographic coordinates of the dam are latitude 20° 13’ 01’’ S, longitude 43° 28’ 10’’ W, and altitude 893 m.

Three other drainage lysimeters were filled with gravel and sand at the bottom and completed with soil classified as *Latossolo Vermelho Amarelo* (Oxisol). Each lysimeter was equipped with a bottom drain to collect the drained water. Tailings and soil samples were collected for physical and chemical characterization. The physical analysis (Table 1) was performed at the Soil Physics Laboratory and the chemical analysis (Table 2) was performed at the Soil, Plant Tissue, and Fertilizer Analysis Laboratory, both belonging to the Department of Soils, Federal University of Viçosa - UFV. The field capacity and permanent wilting point humidity data were obtained at the Soil Physics Laboratory of the Reference Center for Water Resources - DEA/UFV.

TABLE 1. Physical and hydrological properties of mining tailings and soil used in the experiment.

Sample	Coarse sand	Thin sand	Silt	Clay	ME	FC	PWP	PD	BD	Texture
	----------kg kg^{-1}----------							---g cm^{-3}---		
Tailing	0.109	0.593	0.225	0.074	0.06	0.134	0.016	2.92	1.53	Sandy loam
Soil	0.113	0.093	0.047	0.747	0.29	0.237	0.160	2.60	1.18	Clay

ME – moisture equivalent; FC – moisture at field capacity; PWP – permanent wilting point; PD – particle density; BD – soil bulk density.

TABLE 2. Chemical composition of mining tailings and natural soil used in the experiment.

Sample	pH	P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	SB	t	T	V
	(H_2O)	------mg dm^{-3}-----			----------$cmol_c$ dm^{-3}----------							%
Tailings	4.82	2.9	12	0.0	0.36	0.03	0.0	0.5	0.42	0.42	0.92	45.7
Soil	6.39	4.1	112	0.50	3.40	0.79	0.00	1.9	4.48	4.48	6.38	70.2

Sample	m	ISNa	P-rem	Cu	Mn	Fe	Zn	Cr	Ni	Cd	Pb
	---------%---------		----------mg dm^{-3}----------								
Tailings	0.0	0.00	49.3	0.06	22.3	68.0	0.38	0.15	1.03	0.08	1.10
Soil	0.0	0.03	13.2	0.01	6.8	44.5	1.41	-	-	-	-

SB – sum of bases; t – effective cation exchange capacity; T – cation exchange capacity at pH 7.0; V – base saturation index; m – Al saturation; ISNa – sodium saturation index; P-rem – remaining phosphorus.

Pasture implantation

The experiment lasted six months, beginning with the sowing and establishment of pasture for 60 days. At the end of this period, the pasture was cut to a height of 0.25 m. Then, irrigation depths were applied for four cycles, with a fixed cutting age of 30 days. Before sowing, 1.21 t ha^{-1} of lime was applied to the mining tailings to correct their acidity. The tailings received implantation fertilization of 70 kg ha^{-1} P_2O_5 and 60 kg ha^{-1} K_2O, using simple superphosphate and potassium chloride, respectively. The soil needed no acidity correction and received implantation fertilization of 70 kg ha^{-1} P_2O_5 from simple superphosphate.

Sowing was performed using 12 kg ha^{-1} seeds with commercial coating, harvested in the 2017/2018 season with 85% germination, 60% purity, and 51% cultural value. The seeds and phosphate fertilizer were manually applied in rows spaced 0.28 m apart at a depth of 0.02 m, with potassium fertilizer added after seedling emergence.

Maintenance fertilization was performed between cutting and regrowth cycles, with a nitrogen dose of 150 kg ha^{-1} N using urea. Simple superphosphate was used for phosphate fertilization with a dose of 30 kg ha^{-1} P_2O_5, and potassium chloride was used for potassium fertilization with a dose of 200 kg ha^{-1} K_2O. The topdressing fertilization was split twice per cycle and applied by broadcasting on the soil and tailings surface, followed by irrigation.

A soil conditioner, TerraCotten, was added as an additional treatment. It consists of a mixture of hydro-absorbent polymers, fertilizers, and growth stimulators (Melo et al., 2005). A dose of 0.10 kg m^{-2} was distributed between the planting rows to avoid disrupting the root system. The maximum depth of application was 0.20 m

Irrigation management

To ensure seed germination and establish uniformity in the pasture, uniform irrigation was performed at the start of the experiment. To maintain uniformity of the treatments, daily irrigation management was conducted using drainage lysimeters. The irrigation depth applied was 120% of the crop evapotranspiration (ETc). This management was performed in the morning, where the volume drained from the previous day was subtracted. The difference was considered as the volume required to replace 100% of the crop evapotranspiration, following [eq. (1)].

$$\mathrm{ETc} = \mathrm{I} - \mathrm{D} \tag{1}$$

Where:

ETc - crop evapotranspiration (mm d^{-1});

I - irrigation depth corresponding to 120% of ET_c (mm d^{-1});

D - drained water depth (mm d^{-1}).

From the reference depth (100% of the ETc), irrigations were performed in the other lysimeters as a function of the equivalent percentage of each treatment. The depths were converted into the volume by manually distributing water with a watering can over the area of lysimeters.

Rainfall was not considered in the water budget, as lysimeters were under a wooden structure roofed with transparent plastic (1.60 x 1.20 m). The structure was positioned at 0.60 m from the soil surface and was placed only in times of rain, removing it soon afterward to avoid plastic interference with plant development.

During the four cutting cycles, data on average daily temperature, relative air humidity, solar radiation, and rainfall were obtained from the Brazilian National Institute of Meteorology (INMET) database, whose automatic weather station was set up at distances of 750 and 24 meters horizontally and vertically, respectively, from the experiment site.

Shoot and root dry masses

Shoot dry mass (SDM) was measured in each cycle and each lysimeter, collecting a sample using a 0.25-m² square frame. All material within the frame and up to 0.25 m height was packed in paper bags and dried under a forced air circulation oven at 55 °C for 72 hours (Detmann et al., 2012). The parameter was calculated by summing up the yield of each repetition in the four evaluated cycles. The results were expressed in kilograms per square meter (kg m^{-2}).

After the last cut, root samples were collected from each lysimeter for examination. This was done using a cylindrical PVC tube with a 0.19 m diameter and 0.35 m height, totaling a volume of 0.0105 m³. The surface was cleared and the tube was inserted into the ground until it was level with the surface.

A trench was dug around the tube to ensure easy removal without disturbing the collected sample. The material inside the tube was then rinsed to separate and clean the roots. Afterward, the samples were placed in paper bags and taken to a laboratory for dry mass determination in a forced-air oven at 55° C for 72 hours. It should be noted that high-temperature drying can cause the loss of volatile or complex compounds in fibrous materials that contain protein, which may compromise further chemical analysis (Detmann et al., 2012). Root dry mass (RDM) was determined for each lysimeter and expressed in kilograms per cubic meter (kg m^{-3}).

Experimental design and data analysis

The experiment involved five irrigation treatments: D40, D60, D80, D100, and D120, which correspond to 40, 60, 80, 100, and 120% of the ETc, respectively. Two additional treatments were also conducted, including grass grown in tailings with soil conditioner (CD40), with irrigation depth corresponding to 40% of the ETc, and grass grown in natural soil (NS), with irrigation depth corresponding to 100% of the ETc. The experiment was designed as a completely randomized study with three replicates for each treatment.

Data were analyzed using analysis of variance and regression. To assess the impact of the five irrigation depths, regression analysis was applied. The models were selected based on the significance of regression coefficients, using a t-test at a 5% probability level, in the coefficient of determination (R^2 = SQ regression/SQ treatment), and in the behavior of the studied phenomena.

To compare the means of all treatments, the Tukey test was used, at a 5% significance level. All statistical analyses were performed in the RStudio program using the ExpDes.pt package (Ferreira et al., 2018).

RESULTS AND DISCUSSION

Accumulated rainfall for the four cycles was recorded as 162, 124, 115, and 53 mm in that order. Relative humidity ranged between 66 and 96%, with the highest and lowest readings on the second and hundredth fourth day, respectively. The highest daily average temperature reached 25.5°C on the third day during the first cutting cycle of Xaraés grass. One day earlier, the highest level of solar radiation was recorded (322.40 W m^{-2}). In turn, the lowest radiation (12.15 W m^{-2}) coincided with the day when the highest relative humidity was registered. This was marked by a low-intensity rain event that took place for most of the day. It is noteworthy that the lowest average daily temperature (17°C) occurred on the 115th day of evaluation.

The results of our analysis showed a positive linear relationship between irrigation depth and shoot dry mass (SDM) ($p<0.01$) in the range of 40% to 120% of ETc. The highest average SDM (1.41 kg m^{-2}) was obtained from the D120 treatment. This represents a 2.06-fold increase in productivity compared to the D40 treatment, which had the lowest average SDM of all treatments (Figure 1).

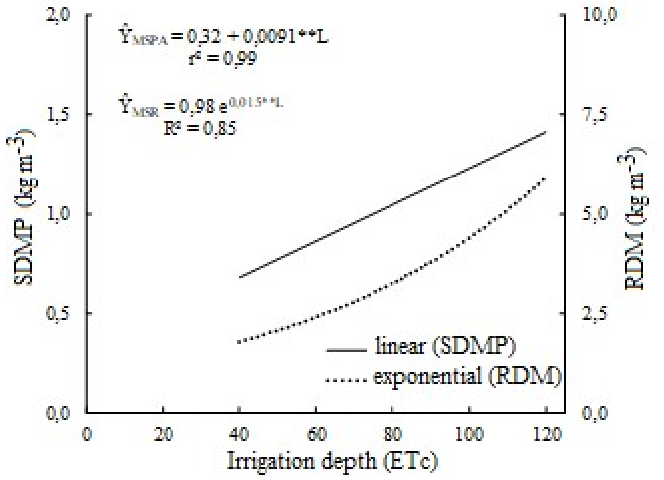

FIGURE 1. Shoot (SDM) and root (RDM) dry masses of Xaraés grass under different irrigation depths and grown in iron mining tailings. ** Significant at 1% probability by t-test

Our findings indicated a positive and exponential relationship between irrigation depths and root production ($p<0.01$). Within the range of 40% to 120% of ETc, an increase in water replacement led to an exponential growth in root dry mass. The D120 treatment showed the highest estimated production of root dry mass (5.94 kg m^{-3}). This represents a 3.32-fold increase compared to the D40 treatment, which had the lowest estimated root dry mass production (Figure 1).

The results of the Tukey test analysis (Table 3) showed that the D120 treatment produced the highest shoot dry mass (SDM) with an average of 1.42 kg m^{-2}. This result was statistically significant and superior to the other treatments, including D80 (1.02 kg m^{-2}), D60 (0.86 kg m^{-2}), D40 (0.69 kg m^{-2}), and CD40 (1.07 kg m^{-2}).

TABLE 3. Shoot (SDM) and root (RDM) dry masses of Xaraés grass after the four cutting cycles grown in mining tailings and under different irrigation depths (D40, D60, D80, D100, and D120), tailings with soil conditioner (CD40) and natural soil (NS)

Treatment	SDM (kg m^{-2})	RDM (kg m^{-3})
D40	0.69 d	2.15 c
D60	0.86 cd	2.27 c
D80	1.02 bc	2.70 c
D100	1.24 ab	3.70 bc
D120	1.42 a	7.52 a
CD40	1.07 bc	5.35 abc
NS	1.28 ab	6.84 ab
[1]CV	10.09	28.17

Means followed by the same lowercase letter in the column do not differ from each other by the Tukey test at a 5% significance level. [1]Coefficient of variation (in %).

Our observations showed that D100, in which grass was grown under conditions of iron mining tailings, had an SDM yield equal to that of NS, where plants were grown in natural soil. Both treatments received the same amount of water.

The highest root production was achieved in D120, with an average of 7.98 kg m^{-3} of roots. In contrast, D40, D60, and D80 produced lower RDM, with averages of 2.03, 2.50, and 2.70 kg m^{-3}, respectively. No significant differences were observed among these treatments.

Moreover, the soil conditioner affected SDM productivity. The plants treated with CD40 had the same average yield as those treated with D80, which received twice as much water. The plants treated with CD40 also produced more than those treated with D40, even though both received the same irrigation depth.

As for root growth, the soil conditioner had a higher RDM than D40, which used the same amount of water. Additionally, NS was also notable as it produced the second-highest RDM, which was surpassed only by D120, in which the largest amount of water was used. This suggests that under iron mining tailings, root production is only better than in natural soil when water replacement reaches 120% of the crop evapotranspiration.

Cheruiyot et al. (2018) found that Xaraés grass was one of the cultivars least affected by severe water stress while still maintaining high biomass productivity when studying the effects of water stress on 18 accessions of the genus *Urochloa*. This makes Xaraés grass suitable for areas with limited water availability, such as those affected by iron mining tailings with unfavorable conditions for plant growth.

Pezzopane et al. (2015) evaluated the effect of water deficit on four *U. brizantha* cultivars (Xaraés, Paiaguás, Marandu, and Piatã) and observed a reduction in both shoot and roots of plants under water stress. The difference between water deficit and control treatments for the cultivar Xaraés was 46% in shoot dry mass and 51% in root dry mass

Stumpf et al. (2017) conducted a study on the recovery of a coal mining-degraded area and compared root attributes (density, volume, length, and root area) among four grass species. They found that one species of the genus *Urochloa*, similar to the species used in our study, performed better and showed potential for restoring the physical attributes of degraded soils.

Coello et al. (2018) conducted an experiment on degraded area revegetation using tree species in Spain and found that the use of a soil conditioner was effective in promoting root growth and plant establishment in situations of limited moisture and coarse-textured soils, similar to those found in mining tailings. The results they presented support the effectiveness of soil conditioners in these challenging growing conditions.

Iron mining tailings differ from natural soil in terms of physical attributes, particularly soil texture, and structure, which affects soil water retention. Pore diameter plays a role in regulating soil water retention, as micropores retain water while macropores provide soil aeration, giving soil structure control over soil porosity (Totsche et al., 2018).

The role of biotic processes in aggregation is important, as the microbiota plays a key role in breaking down dead plant roots and their exudates (Baumert et al., 2018). In this sense, soil organic matter is crucial for the recovery of degraded areas as it acts as a binding agent for soil particles and helps form aggregates, leading to an improvement in soil structure. A study of corn cultivation in sandy loam soil by Chatterjee et al. (2018) found that practices such as irrigation, adding crop residues to the soil, and proper nitrogen fertilization can help increase the levels of organic carbon in the soil and create better conditions for soil aggregation. Thus, incorporating these practices in iron mining tailings-affected areas can aid in forming soil aggregates and enhancing the structure of the tailings.

Amaral et al. (2012) conducted an experiment using quartzite mining tailings, which have a similar textural classification to the tailings used in our study and found that the highest root yield was 3,540 kg/ha in the treatment that combined 75% mineral fertilizer and 25% organic fertilizer. This combination accelerated root growth and improved the physical properties of quartzite tailings.

In a study on the recovery of a coal mining degraded area, Stumpf et al. (2017) compared root attributes among four species of grasses and found that grass of the genus *Urochloa* had superior performance, making it a promising species for restoring soil physical attributes in degraded areas. However, in this study, lower values of the dry mass of roots were verified than the one found by the authors cited above, which was 13.29 kg m^{-3}.

In a study with Xaraés grass, Bonfim-Silva et al. (2012) found no differences in RDM when soil density was a limiting factor (from 1,000 to 1,600 kg m^{-3}). Therefore, the cultivar can absorb nutrients effectively, even when soil density increases. The highest density value used by the authors was higher than the density of the tailings used in our study (1,530 kg m^{-3}).

The relationship between soil density and porosity, specifically macroporosity, is well established; high soil density leads to low macroporosity, which can restrict plant growth (Krzyzanski et al., 2018). Several factors may have impacted root development in our study, including the physical-chemical properties of the soil and tailings, experimental unit size, tailings layer thickness (0.65 m), root system distribution in the soil and tailings profile, sampled area and depth, and cultivation in lysimeters, which can limit root growth and expansion.

CONCLUSIONS

Our results suggest that Xaraés grass can still produce forage dry mass and develop its root system in unfavorable conditions, due to the characteristics of the iron mining tailings.

An increase in irrigation depth has a beneficial impact on the shoot and root dry masses of Xaraés grass grown in the iron mining tailings.

Optimal shoot and root dry masses can be achieved by applying an irrigation depth equivalent to 120% of the crop evapotranspiration.

Additional research is still needed to evaluate the potential impact of animal trampling and direct grazing conditions on the physical-hydrological properties of the iron mining tailings and the growth of Xaraés grass.

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