stresses

Article

Comparison of the Waterlogging Tolerance and Morphological Responses of Five *Urochloa* spp. Grasses

Rafael Marzall Amaral [1,*], Lesly Astrid Calva Sarango [1], Cristiano Eduardo Rodrigues Reis [1], Tulio Otávio Jardim D'almeida Lins [2], Ericka Beatriz Schultz [3] and Daniel Carballo Guerrero [1]

1 EARTH University, Guácimo 442-1000, Costa Rica
2 Instituto Federal de Rondônia, Colorado do Oeste 76993-000, Brazil
3 Department of Animal Science, Federal University of Viçosa, Viçosa 36570-000, Brazil
* Correspondence: rmarzall@earth.ac.cr

Abstract: Periods with high precipitation and temporary waterlogging in the humid tropics are challenging to the production and survival of some grasses of the genus *Urochloa*. This study aimed to evaluate the tolerance of five types of grass belonging to the genus *Urochloa* under waterlogging conditions through productive and morphological traits. The grasses [*U. arrecta* (Tanner), *U. arrecta* x *U. mutica* (Brachipará), *U. brizantha* cv. Marandú, *U.* hybrid cv. Cayman and *U. humidicola* cv. Llanero] were planted in pots and kept under field capacity for 33 days; then, half of them were submitted to (i) field capacity (33% humidity retention) and the other half were submitted to (ii) waterlogging conditions (2 cm of water above soil level) for 28 days. In this study, Tanner and Brachipará grasses showed higher dry shoot mass under waterlogging conditions, which were followed by Llanero, Cayman, and Marandú, respectively. Llanero, Tanner, and Brachipará presented higher waterlogging tolerance coefficients, 78.7, 76.5, and 64.5, respectively, being less affected than Cayman and Marandú (41.0 and 23.1, respectively). Brachipará, Tanner, and Cayman presented a higher root volume under waterlogging conditions, while Marandú root volume decreased by 88.77%. The Tanner, Brachipará, and Llanero genotypes were more tolerant to poorly drained or waterlogged soils than Cayman and Marandú genotypes.

Keywords: flooding tolerance; morphogenesis; root dimensions; *U. arrecta*; *U. arrecta* x *U. mutica*

check for updates

Citation: Amaral, R.M.; Sarango, L.A.C.; Reis, C.E.R.; Lins, T.O.J.D.; Schultz, E.B.; Guerrero, D.C. Comparison of the Waterlogging Tolerance and Morphological Responses of Five *Urochloa* spp. Grasses. *Stresses* **2024**, *4*, 320–329. https://doi.org/10.3390/stresses4020020

Academic Editors: Julietta Moustaka and Michael Moustakas

Received: 28 February 2024
Revised: 26 April 2024
Accepted: 29 April 2024
Published: 8 May 2024

1. Introduction

The humid tropic zone of Costa Rica experiences common heavy precipitation events, with daily totals exceeding 50 mm and monthly totals ranging between 300 and 500 mm (EARTH University Climatological Station, 2021-own data). This prolonged rain can lead to soil waterlogging, reducing the exchange of gases between the soil and the atmosphere, causing oxygen deprivation in the rhizosphere [1,2]. The reduced gas exchange can also negatively impact plant physiology directly and the photosynthetic process indirectly. Oxygen deficiency influences plant root respiration, which is essential for nutrient uptake and growth. Disruptions in gas exchange under waterlogged conditions impair stomatal function and may lead to anaerobic respiration in the roots. These effects can lead to chlorophyll degradation and premature leaf senescence, ultimately leading to plant death in non-adapted species and cultivars [3,4].

Some grasses from the *Urochloa* (syn. *Brachiaria*) genus, which encompasses a variety of species, hybrids, and cultivars with varying levels of environmental adaptation [5,6], hold potential for use in these high-humidity areas. Some species, such as *U. brizantha* and *U. ruziziensis*, are known for their tolerance to water deficit but struggle in poorly drained soils and prolonged waterlogging [7,8]. Other genotypes, such as *U. humidicola* cv. Llanero [9,10], *U. hybrid* cv. Cayman [11], *U. arrecta* (Tanner grass), and *U. arrecta* x *U. mutica* (Brachipará grass) [12–14], are recognized as more suitable for humidity areas.

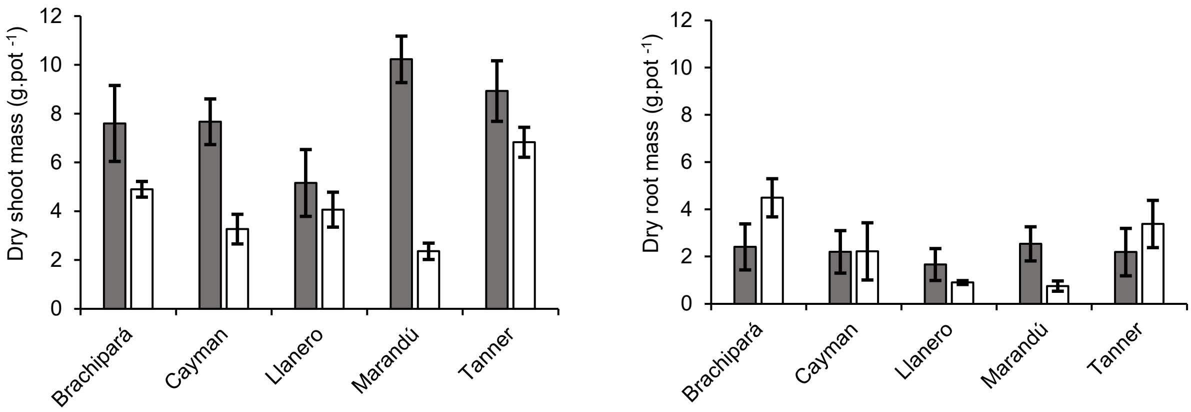
Tanner and Brachipará grasses have not been part of genetic improvement programs, but they are frequently found inside water channels and muddy areas [12]. The genotypes Llanero and Cayman are the results of genetic breeding programs conducted at CIA and CIAT [11,15]. However, it is unclear which grasses exhibit the highest tolerance to waterlogging conditions and how much their production and morphological traits are affected.

Therefore, this study aimed to evaluate the tolerance of five *Urochloa* types of grass under waterlogging conditions and determine the effect on productive and morphological traits.

2. Results

2.1. Biomass and Waterlogging Tolerance Coefficient

The results demonstrate that the soil moisture content and genotype have a significant interaction ($p = 0.016$) on dry shoot mass (Figure 1). Marandú showed a reduction of 76.9% of dry shoot mass, while Tanner and Brachipará grasses exhibited reductions of 23.5 and 35.5%, respectively, obtaining the highest dry shoot mass under waterlogging conditions. The waterlogging tolerance coefficients were calculated as 23.1% for Marandú and 41.0% for Cayman, which were the lowest values. On the other hand, Brachipará, Tanner, and Llanero demonstrated higher values for the waterlogging tolerance coefficient, with 64.5%, 76.5%, and 78.7%, respectively. However, no significant interaction or individual main effects were observed for dry root mass (Figure 1). It was noted that the Tanner and Brachipará genotypes tended to have more dry root mass ($p = 0.072$) under waterlogging conditions compared to field capacity, while other genotypes showed no such tendency.



G: *, SMC: ***, G x SMC: *
(**a**)

G: ·, SMC: n.s., G x SMC: n.s.
(**b**)

Figure 1. (**a**) Dry shoot mass (g·pot^{-1}) and (**b**) dry root mass (g·pot^{-1}) of five *Urochloa* genotypes under two soil moisture contents (field capacity—gray bar and waterlogging—white bar). Wide vertical bars indicate the mean, and thin vertical bars indicate standard-error values. Different letters indicate differences ($p \leq 0.05$, Tukey test). Where G is genotype, SMC is soil moisture content, and G x SMC is the interaction between genotype and soil moisture content. F-test significance code, n.s. ($p > 0.1$), · ($p \leq 0.1$), * ($p \leq 0.05$), and *** ($p \leq 0.001$).

2.2. Root Dimensions

The interaction was identified for the variables root area ($p = 0.036$) and root volume ($p = 0.013$), according to Table 1. The genotypes Brachipará, Cayman, and Tanner showed an increase in both traits under waterlogging conditions, while Marandú and Llanero exhibited a decrease. Marandú had a notably higher root superficial area and volume at field capacity than Tanner grass under the same conditions. During the evaluation period, it was observed that Tanner and Brachipará developed aerial roots in response to waterlogging, as seen in Figure 2, which was not seen in the other genotypes. No significant interactions or independent effects on the average root diameter were observed under these treatments.

Table 1. The average and F-test significance of root area ($mm^2 \cdot plant^{-1}$), diameter (mm), and volume ($mm^3 \cdot plant^{-1}$) of five *Urochloa* genotypes under two soil moisture contents: field capacity and waterlogging.

	Genotypes					F-Test		
Item	**Brachipará**	**Cayman**	**Llanero**	**Marandú**	**Tanner**	**G**	**SMC**	**G x SMC**
Root area ($mm^2 \cdot plant^{-1}$)								
Field capacity	5.817	5.349	12.524	21.427	3.822	n.s.	n.s	*
Waterlogging	19.010	9.231	8.554	9.075	12.465			
Diameter (mm)								
Field capacity	0.603	0.602	0.584	0.637	0.584	n.s.	n.s.	n.s.
Waterlogging	0.584	0.687	0.634	0.647	0.787			
Volume ($^{-1}$) $mm^3 \cdot$plant								
Field capacity	2.537	2.292	5.063	15.002	1.515	n.s.	n.s	*
Waterlogging	11.963	6.235	4.550	1.685	7.228			

Where G is genotype, SMC is soil moisture content, and G x SMC is the interaction be-tween genotype and soil moisture content. F-test significance code, n.s. ($p > 0.1$) and * ($p \leq 0.05$).

Figure 2. Example of adventitious aerial roots in Tanner grass (*Urochloa arrecta*) at day 28 in waterlogging conditions.

2.3. Morphogenesis

Findings revealed a significant interaction between the leaf elongation rate (LER) and average leaf length (ALL) in the five genotypes under study with a *p*-value of less than 0.001 (Figure 3). Analysis of the results showed that LER and ALL in Brachipará, Cayman, and Marandú were reduced in response to waterlogging conditions. However, the Llanero and Tanner genotypes showed no difference in LER and ALL when grown under either waterlogged or non-waterlogged soil conditions.

The results also showed that the leaf appearance rate (LAR), the number of green leaves, the stem elongation rate (SER), and the final stem length (FSL) did not exhibit a significant interaction. Therefore, the main effects were analyzed independently (Figure 3). Waterlogging conditions were observed to decrease both LAR and the total number of green leaves. However, Brachipará and Tanner's genotypes demonstrated higher values in both variables. SER and FSL were also higher for the Brachipará and Tanner genotypes than the other genotypes and were not affected by soil moisture.

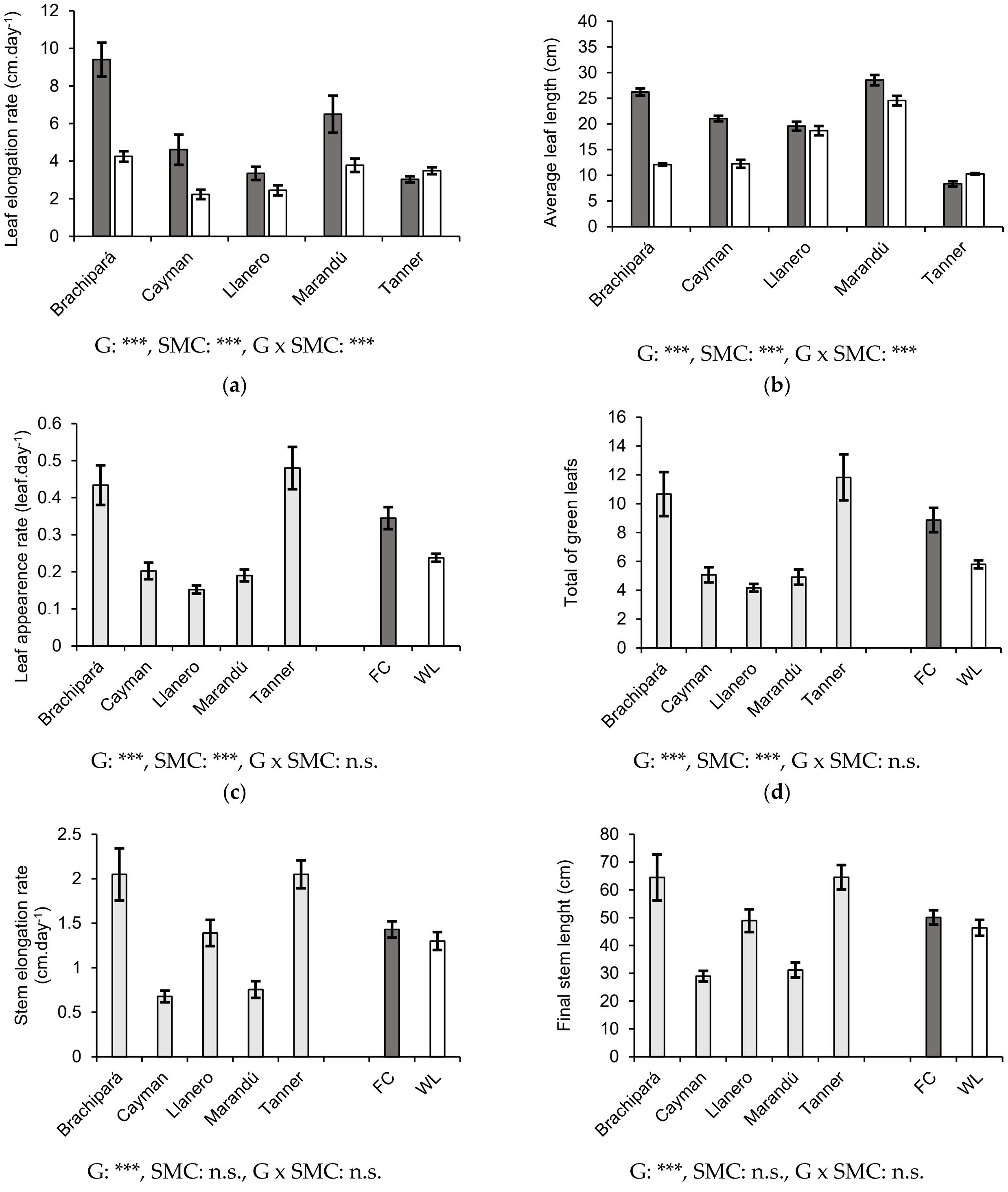


Figure 3. (**a**) Leaf elongation rate (cm.day^{-1}), (**b**) leaf length (cm), (**c**) leaf appearance rate (leaf.day^{-1}), (**d**) total of green leaves, (**e**) stem elongation rate (cm.day^{-1}), and (**f**) final stem length (cm) analyzed as a function of main effects: *Urochloa* genotypes (light gray bars) and soil moisture contents (field capacity (FC)– dark gray bar and waterlogging (WL)—white bar). Wide vertical bars indicate means, and thin vertical bars indicate standard-error values. Different letters indicate differences ($p \leq 0.05$, Tukey test). Where G is genotype, SMC is soil moisture content, and G x SMC is the interaction between genotype and soil moisture content. F-test significance code, n.s. ($p > 0.1$) and *** ($p \leq 0.001$).

As shown in Figure 4, the number of green tillers increased in field capacity conditions by day 28 and tended to remain stable in waterlogging conditions for all genotypes. The Llanero and Cayman genotypes showed a more consistent and similar number of green tillers without significant differences.

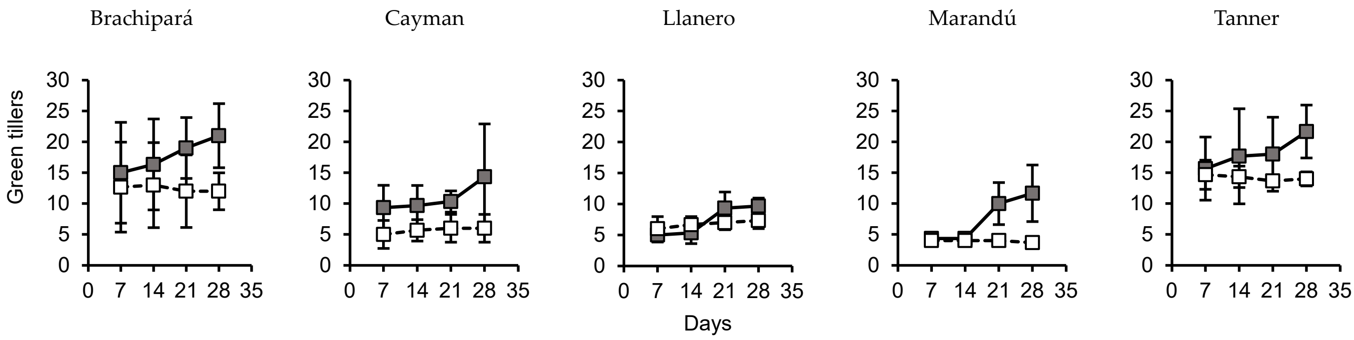


Figure 4. Green tillers per pot as a function of recovery days of five *Urochloa* genotypes: Brachipará, Cayman, Llanero, Marandú, and Tanner under two soil moisture contents (field capacity—solid line with gray squares and waterlogging—dashed line with white squares). Vertical bars indicate the confidence interval (95%).

2.4. SPAD Index, Nitrogen Concentration, and Total Nitrogen

The results of the study showed a strong interaction ($p < 0.000$) between the SPAD index as a function of genotype and soil moisture content, as demonstrated in Table 2. When the soil moisture content was at field capacity, the Llanero and Marandú genotypes showed significantly higher SPAD indices with values up to 10 units higher than the other three genotypes. On the other hand, the Brachipará and Tanner genotypes had higher SPAD indices under waterlogging conditions compared to field capacity, while the other genotypes showed the opposite trend.

Table 2. SPAD index, nitrogen concentration, and total nitrogen of five *Urochloa* genotypes under two soil moisture contents: field capacity and waterlogging.

	Genotypes					F-Test		
Item	**Brachipará**	**Cayman**	**Llanero**	**Marandú**	**Tanner**	**G**	**SMC**	**G x SMC**
SPAD index (dimensionless)								
Field capacity	25.67	28.15	38.39	38.47	27.94	***	***	***
Waterlogging	28.37	26.98	29.54	28.17	31.13			
Nitrogen concentration ($g \cdot kg^{-1}$)								
Field capacity	1.22	1.01	1.71	1.23	1.31	*	***	·
Waterlogging	0.92	0.89	0.93	0.83	0.84			
Total nitrogen ($g \cdot plant^{-1}$)								
Field capacity	0.09	0.08	0.08	0.13	0.11	*	***	*
Waterlogging	0.04	0.03	0.04	0.02	0.06			

Where G is genotype, SMC is soil moisture content, and G x SMC is the interaction between genotype and soil moisture content. F-test significance code, · ($p \leq 0.1$), * ($p \leq 0.05$), and *** ($p \leq 0.001$).

The study also found that waterlogging harmed all genotypes' nitrogen concentration. A significant interaction ($p = 0.015$) was also observed for total nitrogen, indicating that some genotypes were more affected by waterlogging conditions. Among the genotypes, Llanero, Tanner, and Brachipará were the least affected by waterlogging with reductions of 55.96%, 50.26%, and 48.59% of total nitrogen, respectively. Meanwhile, Cayman and Marandú were more affected with reductions of 64.65% and 84.33% of total nitrogen, respectively.

3. Discussion

The results of this study provide valuable insights into the waterlogging tolerance and morphological responses of five *Urochloa* spp. grasses. The results showed that all five *Urochloa* spp. grasses exhibited varying degrees of waterlogging tolerance, revealing that Llanero, Tanner, and Brachipará were more resilient, producing more than 64% of their dry shoot mass under these conditions. In contrast, Marandú produced only about a quarter of its dry shoot mass. In situations of hypoxia (low O_2 concentration) and anoxia (O_2 absence), plant respiration processes become compromised, leading to the generation of toxic compounds that disrupt metabolic pathways. This in turn triggers the production of reactive oxygen species (ROS), causing oxidative damage [16]. The primary consequences for vulnerable plants include disturbances in root hydraulic conductivity, constraints on stomatal conductance, and a decline in photosynthesis, ultimately resulting in reduced growth and biomass production. The dry shoot mass verified in these genotypes is the result of their phenotypical plasticity, anatomical and morphological adaptations, such as their hollow stems, the presence of adventitious aerial roots, and a tendency to increase their root dry biomass ($p = 0.07$) (Figure 1). Tanner and Brachipará grasses are classified as amphibious because of their anatomical and morphological adaptations to humidity zones [12]. The adventitious roots found on Tanner and Brachipará promote gas exchange and nutrient absorption, allowing normal growth and development [4]. Under waterlogged conditions, tolerant plants synthesize more ethylene, which orchestrates the balance between gibberellic acid and abscisic acid, thereby promoting shoot elongation and the formation of adventitious roots [17].

These anatomical and morphological adaptations favor the access and diffusion of atmospheric O_2 into the internal cells [18]. The Llanero genotype did not present a reduction in aerial dry biomass under waterlogging conditions. The low values observed for aerial biomass of the Llanero genotype are related to the natural slowness in the establishment process [19]. Caetano and Dias-Filho [20] evaluated different accessions of *U. brizantha*, and they found significant reductions of root dry biomass for Marandú but not for the other four accessions and cultivars of *U. brizantha* under flooding conditions.

The suppression of leaf elongation rate and average leaf length of Brachipará, Cayman, and Marandú indicates their more intense sensibility to waterlogging conditions than Llanero and Tanner, which do not present reductions in leaf traits as a function of waterlogging. Duarte et al. [21] found LER of 4.30 cm.day^{-1} and 4.28 cm.day^{-1} for the Llanero genotype at 50% soil water retention capacity and under 1 cm of water above the soil, respectively, but at 5 cm of water above the soil, the LER reduced to 2.69 cm.day^{-1}. Comparing *U. brizantha* cv. Marandú, *U. decumbens*, and *U. humidicola* under flooding conditions, Dias-Filho and Carvalho [22] found significant reductions in leaf elongation rates since the first day of evaluation for Marandú but not for *U. decumbens* and *U. humidicola* genotypes. This information illustrates the variate response of grasses to flooding conditions at different intensities and duration of stress. Even being related plants, Brachipará, a spontaneous hybrid of *U. arrecta* (Tanner) and *U. mutica* [12], performs differently in terms of LER and average leaf length, which justifies the higher biomass verified for Tanner in relation to Brachipará in the waterlogging conditions simulated in this experiment.

The leaf appearance rate, total of green leaves, stem elongation rate, and final stem length were higher for Brachipará and Tanner genotypes, which are prostrate, stoloniferous, and very aggressive species [12,13]. Lower average values for the leaf appearance rate and a total of green leaves, verified as a function of waterlogging conditions, are consequences of the reduction in aerobic respiration and photosynthesis. The hampered availability of O_2 and CO_2 to cells of organs surrounded by water reduces cellular energy and carbohydrate shortages that limit growth. It could alter plant development, producing a more intense effect in less adapted plants [18].

The number of green tillers evaluated as a function of the recovering days and soil moisture content demonstrates a clear pattern. Plants in a state of stress due to excess water tended not to multiply their tillers, being waterlogging tolerant or not. Tiller multiplication is a reflex of the natural growth process. It is directly related to environmental and endogenous factors: for example, the presence and access to soil nutrients (primarily nitrogen and phosphorous), light intensity, temperature and adequate humidity, auxins, and photoassimilates [23]. Beloni et al. [7] discuss that during waterlogging, plants may favor the partitioning of photoassimilates to the root system and the accumulation of organic reserves, which can increase plant resilience after the cessation of stress. Voesenek and Bailey-Serres [18] examined the survival strategies of plants in flooded situations and concluded that survival is negatively correlated with growth, explaining the lower growth rates they found. In this experiment, the proliferation of tillers was interrupted to increase the chances of survival. Studying accessions of *Urochloa* grasses, Caetano and Dias-Filho [20] found reductions in the mean number of tillers for four of six accessions under flooding conditions compared to well-drained conditions.

Brachipará and Tanner present a higher SPAD index in waterlogged conditions. These results indicate that the chlorophyll content and the level of photosynthesis activity are related to the higher aerial biomass (Figure 1) and leaf appearance rate (Figure 4), being another indicator of the Brachipará and Tanner genotypes' ability to produce under waterlogging conditions. The Llanero and Cayman genotypes were relatively stable in response to this variable. Cardoso et al. [15], studying morpho-anatomical adaptations to waterlogging on 12 *U. humidicola* accessions, did not find significant differences in the SPAD index when the plants were in waterlogging. Marandú, as a genotype that is not waterlogging tolerant, presented a significant reduction in SPAD index value. Dias-Filho and Carvalho [22] reported related results; they found a significant reduction in leaf chlorophyll content for Marandú and no reductions for *U. decumbens* and *U. humidicola.*

In non-adapted plants, chlorophyll synthesis is reduced under waterlogging stress conditions, leading to leaf yellowing and senescence. The consequences include a reduced photosynthesis rate and, depending on stress duration, plant death. Jiménez et al. [8] justify that the aerenchymas, present in the Llanero, Tanner, and Brachipará genotypes, allow the transport of atmospheric oxygen from leaves and allow the maintenance of adequate levels of chlorophyll and photosynthetic efficiency under stress conditions, being vital to maintain leaf function and nutrient and water uptakes under waterlogging conditions.

The nitrogen concentration and accumulation results obtained from aerial biomass on day 28 clarify the overall negative effect of waterlogging ($p < 0.000$) on nitrogen uptake. Ren et al. [2], studying nitrogen metabolism and uptake on maize under waterlogging conditions, verified that nitrogen accumulation was significantly reduced in different plant organs after waterlogging. This reduction reflects the restriction in root growth and the consecutive disruption in nitrogen uptake, transportation, and distribution, as well as the decrease in the activity of nitrogen metabolism enzymes [2,24].

The findings of this study have important implications for the cultivation and management of these grasses in waterlogged conditions. The soil waterlogging affected all genotypes at different intensities. Tanner, Brachipará, and Llanero genotypes are more tolerant to poorly drained or temporarily waterlogged soils than Cayman and Marandú genotypes. The morphological responses of the *Urochloa* spp. grasses to waterlogging stress also highlight the importance of the careful selection of the genotype to be planted in floodable areas to avoid significant yield losses. Further studies could investigate the physiological and biochemical responses of *Urochloa* spp. grasses to waterlogging stress to gain a deeper understanding of their tolerance mechanisms.

4. Materials and Methods

4.1. Location and Weather Condition

The experiment was conducted at the EARTH University in Limón, Costa Rica (10°12′52.5″ N 83°35′41.9″ W), which is located in the humid tropic at 60 m above sea level. It was developed during the months of June, July, and August, with a relative humidity of 78.51%, and an air temperature of 26.8 °C.

4.2. Materials

Five genotypes of the *Urochloa* genus used as forage crops in humid tropics were evaluated [11,12,14,19]: (i) *U. arrecta* (Tanner grass); (ii) *U. arrecta* x *U. mutica* (Brachipará grass), a spontaneous hybrid; (iii) *U. humidicola* cv. Llanero, (iv) *U.* hybrid cv. Cayman (BR02/1752). *U. brizantha* cv. Marandú, a non-waterlogging tolerant [7,25], was included as a reference grass. The analyzed grasses are acknowledged for their resilience to flooding conditions, yet there is a notable absence of direct comparisons quantifying their respective waterlogging tolerance and affectations.

4.3. Experimental Design and Analysis

The study consisted of a factorial arrangement with five *Urochloa* genotypes and two soil moisture conditions: (i) field capacity (33% humidity retention) and (ii) waterlogging conditions (2 cm of water above soil level) for 28 days, with three replications arranged in a completely randomized design.

Six-liter pots with 5 kg of clayey texture soil were used. Chemical analysis of the used soil presents the following results: pH in water = 5.42; calcium 3.20 cmol·L^{-1}; magnesium = 1.24 cmol·L^{-1}; phosphorus = 15 ppm; potassium = 0.62 cmol·L^{-1}; effective cation exchange capacity = 5.46 cmol·L^{-1}; base saturation = 92.67%. Three vegetative tillers from mature plants were planted per pot. After 14 days of development, one plant per pot was selected to develop in field capacity conditions for an additional 19 days.

At 33 days of planting, all plants were cut 15 cm above the soil, and then the soil moisture content treatments were conducted for 28 days. The volumetric water content was measured with a Fieldscout TDR 300 Soil Moisture Meter (Spectrum Technologies Inc., Plainfield, IL, USA). Field capacity was assumed as 33% of soil moisture content. Flooding treatment was achieved by blocking the pot's drainage holes and maintaining two cm of water sheet above soil level. The plants were kept in a greenhouse with side openings, and both soil water conditions were controlled by the daily manual irrigation.

Plants were harvested at 28 days of regrowth. Shoot and root parts were separated, and roots were washed and air-dried; both components were weighed and dried in a forced circulation oven at 65 °C for 72 h. The waterlogging tolerance coefficient (WTC) that was used to measure each genotype's relative waterlogging tolerance expressed as a percentage is displayed in Equation (1).

$$\text{WTC}(\%) = \frac{\text{Dry shoot mass under waterlogging}}{\text{Dry shoot mass under field capacity}} \times 100\% \quad (1)$$

Approximately 10 g of samples from the fresh roots of each plant was weighed and scanned. The images were treated and analyzed with SAFIRA Software v1.1 [26] to obtain the diameter (mm), area (mm^2·plant^{-1}), and volume (mm^3·plant^{-1}). Data collected from 10 g samples were corrected to total root biomass.

Two tillers per plant were identified using colored flexible plastic ribbons to collect morphological data. The records were taken at 7, 14, 21, and 28 days of regrowth. Measurements were the length of leaf blades (expanding and expanded), the length of pseudo-stems (from soil level to the ligule of the last expanded leaf), the number of live and dead leaves per tillers, and the number of tillers per plant. These measurements were used to calculate the following: leaf appearance rate (LAR—leaves per tiller.day^{-1}); leaf elongation rate (LER—cm per tiller.day^{-1}); stem elongation rate (SER—cm per tiller.day^{-1}); final leaf blade length (FLL—cm.tiller^{-1}); final stem length (FSL—cm); total of green leaves per tiller (NGL—leaves.tiller^{-1}) and the number of green tillers (NGT—tillers·plant^{-1}) as described by Gomide and Gomide [27].

The SPAD index (dimensionless) was measured at day 28 of regrowth in five random expanded leaves per plant using a non-destructive chlorophyll meter (Minolta SPAD-502, Konica-Minolta, Osaka, Japan). The nitrogen content (g·kg^{-1}) was obtained by the Dumas method with TruMac equipment (LECO Corporation, St. Joseph, MI, USA). The total nitrogen (g·plant^{-1}) was given by the multiplication of dry shoot mass (g·plant^{-1}) by nitrogen content (g·kg^{-1}).

4.4. Statistical Analysis

The variables were assessed through an analysis of variance employing a factorial model. The main factors considered were genotype and soil water content. In cases where no significant interaction effect was detected, the means of the main factors were reported separately. Statistical significance was determined when *p*-values were $\leq$0.05 with corresponding F values provided. The data presented as a function of the days were analyzed using a confidence interval (95%). Analysis was performed using Software R version 4.2.1.

5. Conclusions

To summarize, this study aimed to assess the tolerance of five species of *Urochloa* grass to waterlogging conditions based on morphological and productive traits. The results indicated that *U. arrecta* (Tanner), *U. arrecta* x *U. mutica* (Brachipará), and *U. humidicola* cv. Llanero showed greater waterlogging tolerance than *U.* hybrid cv. Cayman and *U. brizantha* cv. Marandú, as demonstrated by their higher shoot dry mass and waterlogging tolerance coefficients. Brachipará, Tanner, and Cayman also exhibited higher root volume under waterlogging conditions, while Marandú showed decreased root volume. Therefore, the study suggests that the Brachipará, Tanner, and Llanero genotypes may be more suitable for pasture improvement in regions with high precipitation and temporary waterlogging in the humid tropics. However, further research is required to understand the mechanisms behind the differences in waterlogging tolerance among these grasses, which could aid in developing more robust and productive pasture systems in the humid tropics.

Author Contributions: Conceptualization, R.M.A. and L.A.C.S.; methodology, R.M.A. and T.O.J.D.L.; formal analysis, C.E.R.R. and D.C.G.; investigation, R.M.A. and L.A.C.S.; resources, C.E.R.R.; writing—original draft preparation, L.A.C.S. and R.M.A.; writing—review and editing, D.C.G., C.E.R.R., T.O.J.D.L. and E.B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was carried out with funding from the EARTH university academic program, project code 19011.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Bailey-Serres, J.; Voesenek, L.A.C.J. Flooding stress: Acclimations and genetic diversity. *Annu. Rev. Plant Biol.* **2008**, *59*, 313–339. [CrossRef]
2. Ren, B.; Dong, S.; Zhao, B.; Liu, P.; Zhang, J. Responses of nitrogen metabolism, uptake and translocation of maize to waterlogging at different growth stages. *Front. Plant Sci.* **2017**, *8*, 1216. [CrossRef]
3. Dias Filho, M.B.; de Freitas, M.V.; Lopes, M.J.d.S.; Cruz, E.D.; Barrios, S.C.L.; do Valle, C.B. *Tolerância Relativa de Híbridos de Brachiaria Decumbens ao Alagamento do Solo*; Embrapa Amazônia Oriental: Belém, Brazil, 2018.
4. Pan, J.; Sharif, R.; Xu, X.; Chen, X. Mechanisms of waterlogging tolerance in plants: Research progress and prospects. *Front. Plant Sci.* **2021**, *11*, 627331. [CrossRef]
5. Hungria, M.; Rondina, A.B.L.; Nunes, A.L.P.; Araujo, R.S.; Nogueira, M.A. Seed and leaf-spray inoculation of PGPR in brachiarias (*Urochloa* spp.) as an economic and environmental opportunity to improve plant growth, forage yield and nutrient status. *Plant Soil* **2021**, *463*, 171–186. [CrossRef]
6. Ruiz, F.L.; Cancino, S.J.; Martínez, J.R.G.; Martínez, Y.B.; Drouaillet, B.E.; Martínez, A.G.L. Dinámica de tallos e índice de estabilidad en cinco cultivares de Urochloa en condiciones semiáridas. *Trop. Grassl-Forrajes Trop.* **2023**, *11*, 1–10. [CrossRef]

7. Beloni, T.; Pezzopane, C.G.; Rovadoscki, G.A.; Fávero, A.P.; Dias-Filho, M.B.; Santos, P.M. Morphological and physiological responses and the recovery ability of Paspalum accessions to water deficit and waterlogging. *Grass Forage Sci.* **2017**, *72*, 840–850. [CrossRef]
8. Jiménez, J.d.l.C.; Cardoso, J.A.; Dominguez, M.; Fischer, G.; Rao, I. Morpho-anatomical traits of root and non-enzymatic antioxidant system of leaf tissue contribute to waterlogging tolerance in Brachiaria grasses. *Grassl. Sci.* **2015**, *61*, 243–252. [CrossRef]
9. Mass Junior, R.; Domiciano, L.F.; Ribeiro, L.F.C.; Pedreira, B.C. Growth responses of nine tropical grasses under flooding conditions. *Trop. Grassl-Forrajes Trop.* **2016**, *4*, 1–7. [CrossRef]
10. Rincón, A.; Flórez, H.; Ballesteros, H.; León, L.M. Efectos de la fertilización en la productividad de una pastura de Brachiaria humidicola cv. Llanero en el Piedemonte de los Llanos Orientales de Colombia. *Trop. Grassl-Forrajes Trop.* **2018**, *6*, 158–168. [CrossRef]
11. Pizarro, E.A.; Hare, M.D.; Mutimura, M.; Changjun, B. Brachiaria hybrids: Potential, forage use and seed yield. *Trop. Grassl. -Forrajes Trop.* **2013**, *1*, 31–35. [CrossRef]
12. de Andrade, C.M.S.; de Assis, G.M.L.; Fazolin, M.; Gonçalves, R.C.; Sales, M.F.L.; Valentim, J.F.; Estrela, J.L.V. *Capim-Tangola: Gramínea Forrageira Recomendada para Solos de Baixa Permeabilidade do Acr*; EMBRAPA Acre: Rio Branco, Brazil, 2009.
13. Alvim, M.J.; Botrel, M.A.; Xavier, D.F. *As Principais Espécies de Brachiaria Utilizadas no País*; EMBRAPA Gado de Leite: Juiz de Fora, Brazil, 2002.
14. Queiroz, D.S.; Casagrande, D.R.; Moura, G.d.S.; Silva, E.A.d.; Viana, M.C.M.; Ruas, J.R.M. Espécies forrageiras para produção de leite em solos de várzea. *Rev. Bras. Zootec.* **2012**, *41*, 271–280. [CrossRef]
15. Cardoso, J.A.; Rincón, J.; Jiménez, J.d.l.C.; Noguera, D.; Rao, I.M. Morpho-anatomical adaptations to waterlogging by germplasm accessions in a tropical forage grass. *AoB PLANTS* **2013**, *5*, plt047. [CrossRef]
16. Hasanuzzaman, M.; Bhuyan, M.H.M.B.; Parvin, K.; Bhuiyan, T.F.; Anee, T.I.; Nahar, K.; Hossen, M.S.; Zulfiqar, F.; Alam, M.M.; Fujita, M. Regulation of ROS metabolism in plants under environmental stress: A review of recent experimental evidence. *Int. J. Mol. Sci.* **2020**, *21*, 8695. [CrossRef]
17. Fukao, T.; Bailey-Serres, J. Ethylene—A key regulator of submergence responses in rice. *Plant Sci.* **2008**, *175*, 43–51. [CrossRef]
18. Voesenek, L.; Bailey-Serres, J. Flooding tolerance: O_2 sensing and survival strategies. *Curr. Opin. Plant Biol.* **2013**, *16*, 647–653. [CrossRef]
19. Peters, M.; Franco, T.; Schmidt, A.; Hincapié Carvajal, B. *Especies Forrajeras Multipropósito: Opciones Para Productores del Trópico Americano*; CIAT: Cali, Colombia, 2011.
20. Caetano, L.P.d.S.; Dias-Filho, M.B. Resposta de seis acessos de capim-braquiária ao alagamento do solo. *Rev. Bras. De Zootec.* **2008**, *37*, 795–801. [CrossRef]
21. Duarte, C.F.D.; Prochera, D.L.; Paiva, L.M.; Fernandes, H.J.; Biserra, T.T.; Cassaro, L.H.; Flores, L.S.; Fernandes, R.L. Morfogênese de braquiárias sob estresse hídrico. *Arq. Bras. Med. Veterinária E Zootec.* **2019**, *71*, 1669–1676. [CrossRef]
22. Dias-Filho, M.B.; Carvalho, C.J.R.D.E. Physiological and morphological responces of *Brachiaria* spp. to flooding. *Pesqui. Agropecuária Bras.* **2000**, *35*, 1959–1966. [CrossRef]
23. Assuero, S.G.; Tognetti, J.A. Tillering regulation by endogenous and environmental factors and its agricultural management. *Am. J. Plant Sci. Biotechnol.* **2010**, *4*, 35–48.
24. Ren, B.; Zhang, J.; Dong, S.; Liu, P.; Zhao, B. Root and shoot sesponses of summer maize to waterlogging at different stages. *Agron. J.* **2016**, *108*, 1060–1069. [CrossRef]
25. Dias-Filho, M.B. *Respostas Morfofisiológicas de Brachiaria spp. ao Alagamento do Solo e à Síndrome da Morte do Capim-Marandu*; EMBRAPA Amazonia Oriental: Belem, Brazil, 2006.
26. Jorge, L.d.C.; Silva, D.d.C. *Safira: Manual de Utilização*; EMBRAPA Instrumentacao: Sao Carlos, Brazil, 2010.
27. Gomide, C.A.M.; Gomide, J.A. Morfogênese de cultivares de Panicum maximum jacq. *Rev. Bras. Zootec.* **2000**, *29*, 341–348. [CrossRef]