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Research Paper

Effect of single and repeated waterlogging events on tropical forage grasses for cut and carry systems

Efecto de eventos únicos y repetidos de anegamiento sobre gramíneas forrajeras tropicales en sistemas de corte y acarreo

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Abstract

The introduction of improved forage cultivars has enhanced nutrition and performance of beef cattle in stall feeding cut and carry systems in Vietnam and other Southeast Asian countries. However, the persistence of these forages can be reduced by flooding and waterlogging conditions in low-lying land during the monsoon season. This pot study was established with 5 waterlogging treatments (control, 10-day single, 10-day cycle, 20-day single, and continuous waterlogging) for an 84-day period following establishment to evaluate the waterlogging tolerance of 7 improved grass cultivars. *Urochloa humidicola* (Rendle) Morrone & Zuloaga, *Paspalum atratum* Swallen. and *Digitaria eriantha* Streud. were most tolerant of waterlogging. Tiller number and dry matter production were negatively affected by cycling and continuous waterlogging in less tolerant species *Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs, *Urochloa* hybrid 'Mulato II' and *Urochloa ruziziensis* (R. Germ. and C.M. Evrard) Crins. This information will assist in providing recommendations for smallholder farmers about which species to grow under repeated or continuous waterlogging.

Keywords: Production, tiller survival.

Resumen

La introducción de cultivares de forrajes mejorados ha mejorado la nutrición y el rendimiento del ganado de carne en sistemas de alimentación estabulada en sistemas de corte y acarreo en Vietnam y otros países del sudeste asiático. Sin embargo, la persistencia de estos forrajes puede reducirse por las condiciones de inundación y anegamiento en tierras bajas durante la temporada de monzones. Este estudio en macetas se estableció con 5 tratamientos de anegamiento (control, tratamiento único de 10 días, en ciclos de 10 días, tratamiento único de 20 días y anegamiento continuo) durante un período de 84 días después del establecimiento para evaluar la tolerancia al anegamiento de 7 cultivares de pastos mejorados. *Urochloa humidicola* (Rendle) Morrone & Zuloaga, *Paspalum atratum* Swallen. y *Digitaria eriantha* Streud. fueron los más tolerantes al anegamiento. El número de macollos y la producción de materia seca se vieron afectados negativamente por el anegamiento cíclico y contínuo en las especies menos tolerantes *Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs, *Urochloa* híbrido 'Mulato II' y *Urochloa ruziziensis* (R. Germ. y C.M. Evrard) Crins. Esta información ayudará a proponer recomendaciones a los pequeños agricultores sobre qué especies cultivar en condiciones de anegamiento continuo o repetido.

Palabras clave: producción, sobrevivencia de macollos.

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Introduction

Beef production in Vietnam, like other parts of Southeast Asia, has traditionally been based on extensive grazing, utilizing native or naturally occurring grasses, legumes and herbs along roadsides or in common areas, and stubble of recently harvested crops. Diets are supplemented with crop residues fed in stalls and supplements offered by cooking 'porridge' (Ba et al. 2014). This system is characterised by high labour inputs (Khanh et al. 2015) and low feed quality (Ba et al. 2015). A lack of both quantity and quality of feed resources is one of the major constraints for beef production in smallholder beef enterprises in South Central Coastal Vietnam (Parsons et al. 2013). Competition for feed resources on common lands (Ba et al. 2013) and the reduction in the area of common lands due to intensification of agriculture and urbanisation (Khanh et al. 2014) have encouraged smallholders to investigate more intensive systems of beef production.

A significant transformation of such systems has occurred in the Ea Kar region of Dak Lak province in the central highlands (Stür et al. 2013). One approach for intensifying the production system has been to grow and harvest improved forages and stall-feed them to cattle. Reallocation of some of the cropping land to intensively grown high yielding and high quality forages has been part of a Vietnamese Government strategy to develop livestock systems. Introduction of improved tropical forage cultivars has been part of research projects for improving beef production in smallholder beef enterprises in Southeast Asia (Lisson et al. 2010; Stür et al. 2013; Ba et al. 2014). A theme of these studies is that establishing forage plantations in close proximity to cattle shelters enables an evolution in the production system from predominantly controlled grazing and feeding of crop residues to stall-feeding of improved forages.

Smallholders that do grow forages in this region of Vietnam most commonly grow local varieties of elephant grass (*Cenchrus purpureus* (Schumach.) Morrone). Farmers who have been exposed to projects focusing on improved species prefer to grow 3 main grasses: Guinea grass (*Megathyrsus maximus* (Jacq.) B.K. Simon & S.W. L. Jacobs) 'TD58', hybrid elephant grass (*C. purpureus* × *C. americanus*) 'VA06' and the *Urochloa* hybrid (*U. ruziziensis* × *U. decumbens* × *U. brizantha*) 'Mulato II' (Ba et al. 2014). Other grass and legume species have been introduced, including *Paspalum atratum* Swallen. 'Ubon', *Stylosanthes guianensis* (Aubl.) Sw. CIAT 184 and *Leucaena leucocephala* (Lam.) De Wit ' Tarramba', but are less preferred by smallholders (Ba et al. 2013; Ba et al. 2014). These smallholder preferences are influenced by the responses of these forage species to the local growing conditions, palatability for cattle and ease of establishment (Ba et al. 2014). In the case of *S. guianensis*, the inability of farmers to extend their forage area with vegetative material and the necessity to save seed are major constraints for smallholders. For leucaena 'Tarramba', inexperience with tree legume forages, need for seedling protection, a relatively long lead time between establishment and use, and difficulties with cutting management in smallholder situations all contributed to poor adoption in some areas (Nam et al. 2015). Rapid establishment and regeneration is one of the key traits leading to the success of the grass family Poaceae (Linder et al. 2018), and is one of the key reasons why introduced grasses have been more successful than legumes.

Soils in the South Central Coastal region of Vietnam are typically deep sands (<5% clay) and deep loamy sands and sandy loams (5–18% clay) (Bell et al. 2015) with low levels of organic carbon. Sandy soils with low clay content and low organic matter tend to have low nutrient holding capacity. This means that regular fertiliser needs to be applied to sustain production. However, the risk of leaching of nutrients applied is high when coupled with heavy rainfall events. These heavy rainfall events can also lead to seasonal inundation, where plants and the soil surface are submerged or flooded for short periods; or waterlogging, where the soil profile remains saturated for long periods. This study focuses on the effects of waterlogging with waterlogging tolerance defined as the plant's ability to survive (maintenance of live tillers) and grow (maintain reasonable growth rates) under waterlogged conditions. Recent studies by Tan and Thanh (2013) have suggested that total rainfall in Vietnam and the incidence of heavy rainfall events is increasing, and that flooding (and hence waterlogging) is occurring more frequently, especially in the South Central Coastal region. Furthermore, flooding is expected to increase in the Southeast Asia region more generally (Hirabayashi et al. 2013).

Under waterlogged conditions oxygen is displaced from the soil pores, and the remainder is rapidly used by plants and other organisms (Setter and Belford 1990; Blom and Voesenek 1996). The reduction in the availability of oxygen in the soil profile is a major constraint to plant growth under waterlogging conditions. Respiration is the most efficient form of energy production for root growth and maintenance and this is reliant on oxygen (Wegner 2010). Setter and Waters (2003) categorised the mechanisms for waterlogging tolerance by trait as; 1. Phenology, 2. Morphology and anatomy, 3. Nutrition,

4. Metabolism including anaerobic catabolism and anoxia tolerance, and 5. Post anoxic damage and recovery. An important anatomic mechanism by which some plants are able to adapt to waterlogging conditions is the formation of aerenchyma cells, which allow greater oxygen flow in the plant (Colmer 2003; Ayi et al. 2019).

Waterlogging can have a number of impacts on tropical forages including reducing dry matter (DM) production and tiller and plant death (Hare et al. 2003). Following the evaluation of several grasses and legume species, Hare et al. (1999) recommended *P. atratum* 'Ubon' for dairy systems in the seasonally waterlogged and seasonally dry regions of northeast Thailand, being more productive than *U. ruziziensis* (R. Germ. and C.M. Evrard) Crins, whose productivity declined over time. Later, Hare et al. (2004) showed that *P. atratum* 'Ubon' had good tolerance to waterlogging, *M. maximus* 'Purple panic' moderate tolerance and *U. ruziziensis* had poor tolerance. *U. humidicola* (Rendle) Morrone & Zuloaga. also exhibits tolerance to waterlogged soils (Dias-Filho and Carvalho 2000; Cardoso et al. 2013).

Forages growing in this region must be tolerant of high temperatures, and the 'toolbox' of forages should include species with tolerance to extremes of both drought and waterlogging, depending on the season. Although it may be possible to have these characteristics in a single species, diversifying the forage species grown could help to reduce risk for smallholders. Each of the above-mentioned forages vary in their adaptation to soil and moisture constraints. Most studies of waterlogging in tropical forages have focussed on a single waterlogging event but there is a paucity of information regarding the effects of repeated events, which may be more reflective of some climatic locations and position within the landscape. The study objectives were to evaluate the effects of both single and repeated waterlogging events on 7 tropical forage grass cultivars and provide an assessment of their suitability for use in Central Coastal Vietnam. The study outputs support the development of guidelines for use of these species and cultivars. The hypotheses were:

- *B. humidicola*, *P. atratum* and *Digitaria eriantha* Streud. are the most tolerant based on previous studies and expert opinion and will be least affected by waterlogging.
- For plants that are sensitive to waterlogging, a repeated cycle of waterlogging is more damaging than the length of time of the waterlogging.

Materials and Methods

Study location

The study was conducted at the Hue University of Agriculture and Forestry (HUAF) campus (16°28' N, 107°34' E), Hue province, in the Central Coastal region of Vietnam. The experiment was conducted in a greenhouse covered in transparent plastic between September and December 2015.

Establishing forages

The 7 grasses used in the experiment were *C. purpureus* × *C. americanus* 'VA06', *Urochloa* hybrid 'Mulato II', *M. maximus* 'TD58', *P. atratum* 'Ubon', *D. eriantha*, *U. ruziziensis* (each collected from a farmer field in Binh Dinh province) and *U. humidicola* (collected from a farmer field in Phu Yen province. Grasses were first established in soil at the HUAF campus and stabilised for a period of 2–3 months, depending on when the tillers were obtained. Healthy tillers were then transferred to 300 mm tall and 270 mm diameter pots. The number of live tillers for each species was recorded at day 0 prior to treatments being applied and is presented in the results section. There were no significant differences in the number of tillers in each pot/treatment of the same species. Pots were filled with a sandy loam textured soil sourced from a local nursery supplier in Hue. Chemical analysis of the soil was undertaken at the Hue University of Agriculture and Forestry soil science department following AOAC International standard methods (AOAC 2012). The results were: pH (KCl) 7.16; OM 2.74%; CEC 12.3 cmol/kg; Total N 0.02 g/kg; Extractable P 0.007 g/kg; Extractable K 0.074 g/kg, indicating low levels of organic matter and major nutrients.

Experimental design

The experiment was arranged in a split-plot design with waterlogging as the main factor (5 levels), grass species as sub-plots (7 species) and 4 replications (blocks). The 5 waterlogging treatments were: 1. Control - water level maintained at 30 mm from the bottom of the pot; 2. 10-day single saturation (10-day single) - water level raised to the soil surface for 10 days, then returned to 30 mm from the bottom of the pot for the remainder of the experiment; 3. 10-day repeated saturation (10-day cycle) - water level raised to the soil surface for 10 days, then returned to 30 mm from the bottom of the pot for 10 days, this cycle was then repeated; 4. 20-day single saturation (20-day single) - water level raised to the soil surface for 20 days, then returned to 30 mm from the bottom of the pot for the remainder of the experiment; 5. Continuous saturation (Continuous) - water level raised to soil surface for the entirety of the experiment (Figure 1). Each of the 4 blocks included 5 randomly placed waterproof polystyrene boxes (with the dimensions; length 1,100 mm, width 700 mm, and depth 500 mm) each with a different waterlogging treatment. Each box (main plot) contained 1 pot of each of the 7 grass species treatments (sub-plots), arranged randomly. The experiment was conducted over 4 × 21 day cycles.

Forage measurement

At the completion of each cycle, the following plant measurements were recorded: biomass production, the total number of live tillers (both primary and secondary), and length of longest vegetative tiller (from crown to tip of the longest expanded leaf).

Grasses were cut to a height of 150 mm above the soil surface on day 21 of each cycle. Tillers were gathered up and extended into a vertical position for measurement of the 150 mm cutting height. After cutting, stem and leaf components of the harvested forage were separated and dried at 105 °C for 48 hours to determine the dry matter yield. At the completion of each cycle, granulated fertiliser (N-P_2O_5-K_2O: 16-16-8) was applied at 0.7 g/pot.

Data analysis

Each output variable was analysed using mixed model procedures in PROC MIXED (SAS 2003) using the REPEATED statement. Waterlogging and species were treated as fixed effects. Non-normal distributions were identified by visual assessment of quantile-quantile plots and distribution of model residuals. Log transformation was applied for DM yields and tiller counts, while a cubed power transformation was used for quantum yield. Significant 3-way interactions were evaluated using the slice option in the lsmeans statement of PROC MIXED, which uses an F test to assess interaction slices, but does not control for family-wise error. For 2-way interactions, the SIMULATE option was used to separate significantly different means. Geometric means used were calculated for transformed data, in lieu of true means.

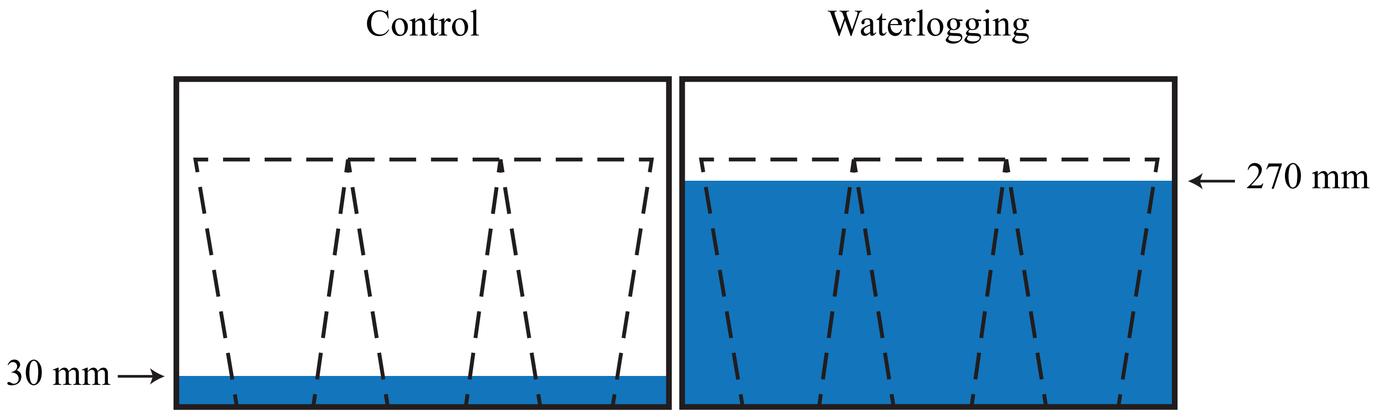

Figure 1. Representation of the water levels under control and waterlogging conditions.

Results

Overview of outputs

There was a significant (P<0.001) species*waterlogging treatment*time interaction on the above ground DM yield, leaf length, leaf DM yield, and the number of live tillers. In addition, all main effects and 2-way interactions were significant at P<0.001. Because 3-way interactions are complex to depict, we present outputs for these variables individually for each species (Figures 2–7). These figures include significances from the SLICE outputs. Significances on the side of the figures show the probability that the output variable for each waterlogging treatment changes over time. Significances on the top of the figures show the probability that the output variable from waterlogging treatments are different at a specific point in time.

Megathyrsus maximus 'TD58'

The above ground DM yield of *M. maximus* 'TD58' in the control treatment appeared to decrease by half between day 21 and day 84; however, this was not significant (P=0.074) (Figure 2a). In contrast, there were significant (P<0.001) decreases in DM yield in both the 10-day cycle and continuous waterlogging treatments throughout the study to <2 g DM/pot by day 84. There were similar patterns for 10-day and 20-day single waterlogging treatments (P=0.053 and P=0.046 respectively), showing a drop in above ground DM yield at the day 63 harvest. The leaf DM results (Figure 2b) reflect those for total above ground DM yield.

The DM yield of the 10-day cycle and continuous waterlogging treatments was reflective of a significant (P<0.001) reduction in live tillers, falling to 2 in the 10-day cycle and 1 in the continuous treatments by day 84 (Figure 2c). Significant (P<0.01) reductions in tiller number were also observed in the control and 20-day single waterlogging treatments but not to the same degree as the 10-day cycle and continuous waterlogging treatments (Figure 2c).

Leaf length was also significantly (P<0.001) negatively affected in both the 10-day cycle and continuous waterlogging treatments (Figure 2d). In contrast, the leaf length significantly (P<0.001) increased in both of the single waterlogging treatments, while there was no significant (P>0.05) change in the control.

Cenchrus purpureus × C. americanus 'VA06'

There was no significant (P>0.05) change in above ground DM yield observed in the control, 10-day single and continuous waterlogging treatments (Figure 3a). However, both the 10-day cycle (P<0.05) and the 20-day single (P<0.001) waterlogging treatments had a positive effect on DM yield over time. The DM yield of the 20-day single treatment increased from 2.4 g DM/pot at day 21 to 10.7 g DM/pot at day 84. The leaf DM results (Figure 3b) broadly reflect those for total above ground DM yield.

In contrast, there was a significant (P<0.01) reduction in live tillers between day 0 and day 84 in all waterlogging and control treatments (Figure 3c), but no significant (P>0.05) difference between treatments at any of the harvest dates, suggesting that there was no effect of waterlogging treatment on live tiller number. The reduction of live tillers occurred mainly between day zero and the first harvest at day 21.

There were significant (P<0.05) effects of all treatments on leaf length over time, although with no clear trend, and no significant (P>0.05) difference between waterlogging treatments post day 21 (Figure 3d).

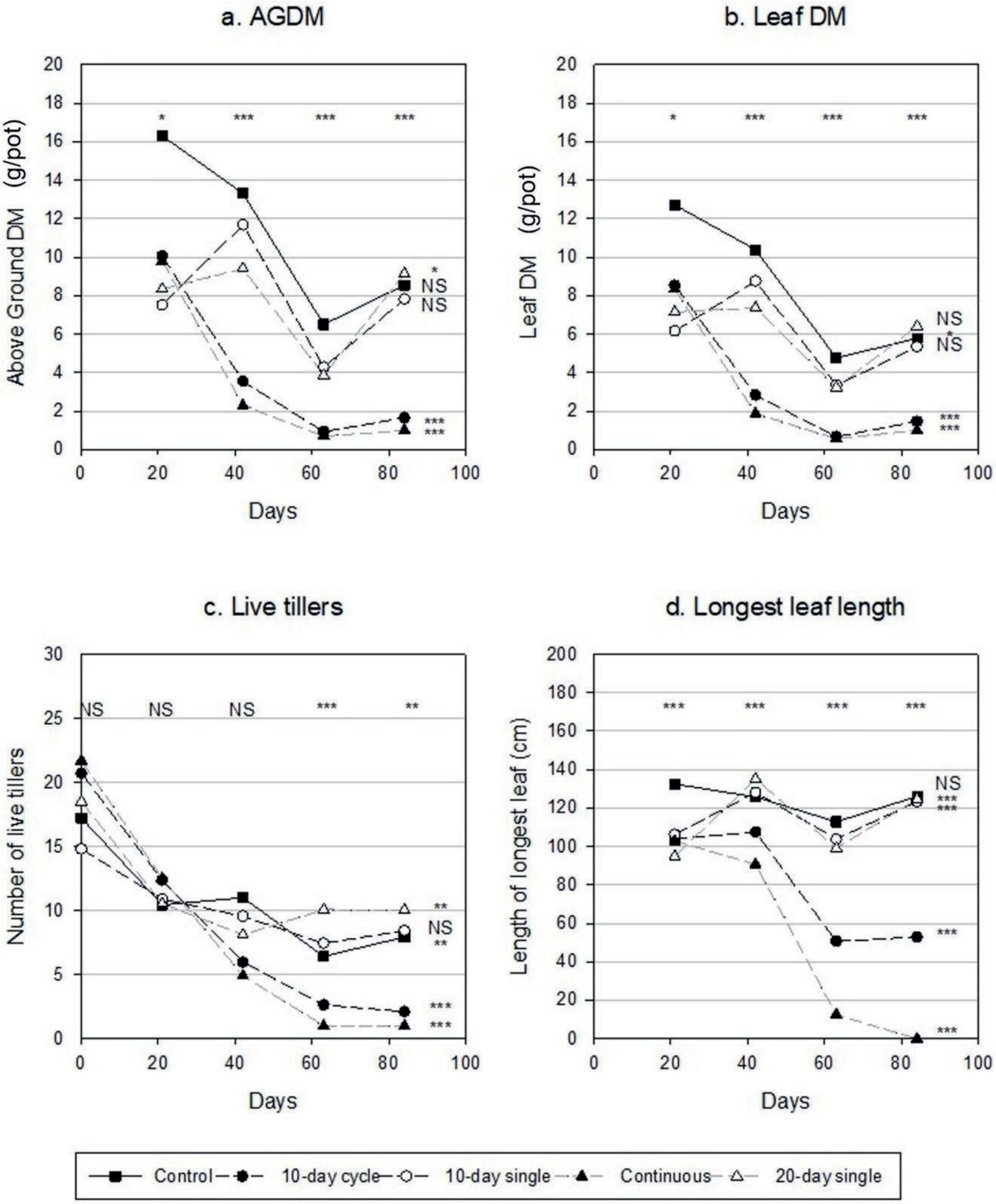

Figure 2. Effects of waterlogging treatments on *Megathyrsus maximus* 'TD58' (a) above ground DM yield, (b) leaf DM yield, (c) number of live tillers, and (d) length of longest leaf. Waterlogging treatments were Control=nil waterlogging; 10-day cycle=repeated 10 days waterlogging then 10 days control conditions; 10-day single=10 days of waterlogging then control conditions throughout; continuous waterlogging conditions; 20-single=20 days of waterlogging then control conditions throughout. Significant differences between waterlogging treatments at each harvest date (x axis) and change within each waterlogging treatment over time (y axis) are represented by NS=not significant (P>0.05); *=P<0.05; **=P<0.01; ***=P<0.001.

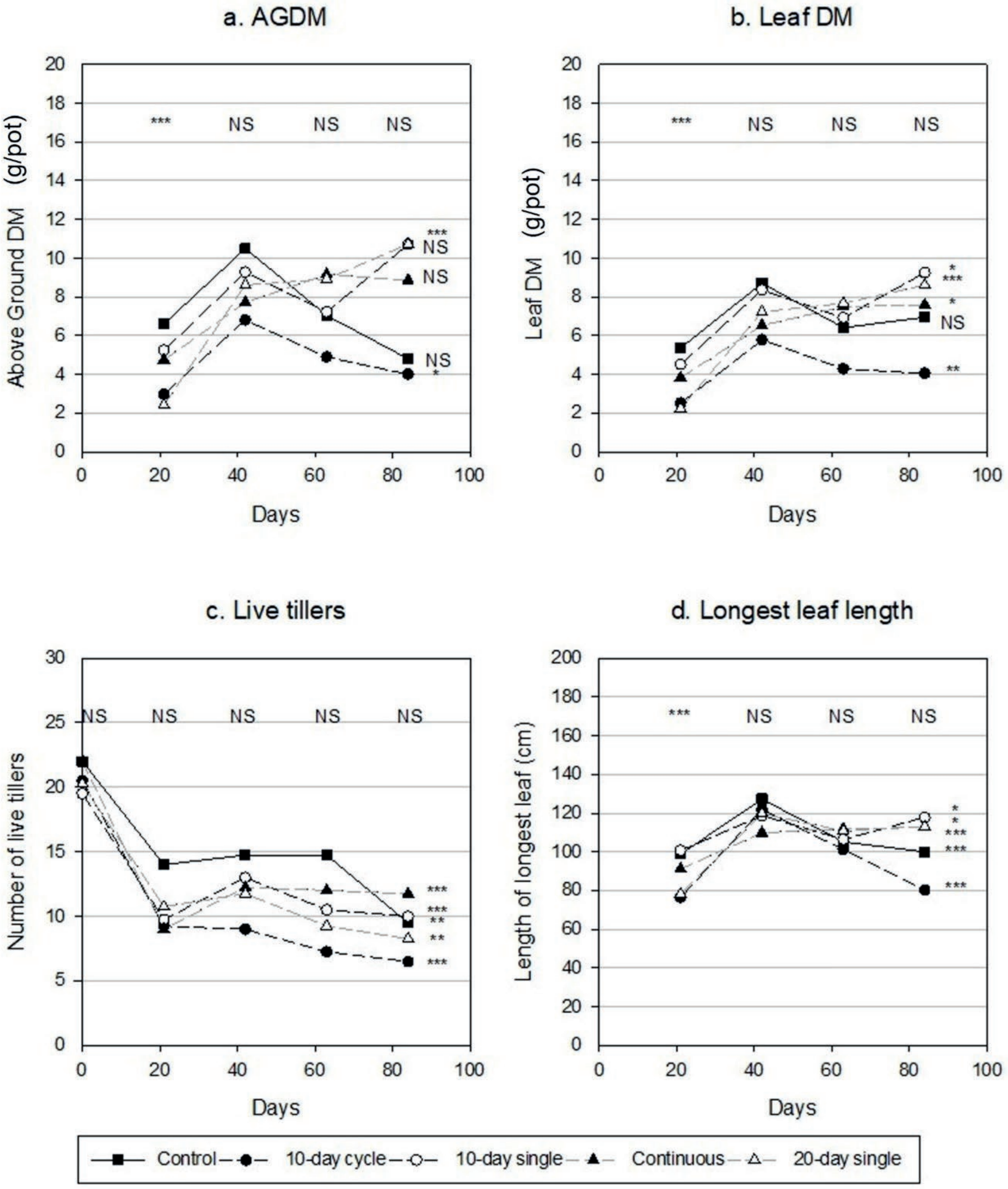

Figure 3. Effects of waterlogging treatments on *Cenchrus purpureus* × *C. americanus* 'VA06' (a) above ground DM yield, (b) leaf DM yield, (c) number of live tillers, and (d) length of longest leaf. Waterlogging treatments were Control=nil waterlogging; 10-day cycle=repeated 10 days waterlogging then 10 days control conditions; 10-day single=10 days of waterlogging then control conditions throughout; continuous waterlogging conditions; 20- single=20 days of waterlogging then control conditions throughout. Significant differences between waterlogging treatments at each harvest date (x axis) and change within each waterlogging treatment over time (y axis) are represented by NS=not significant (P>0.05); *=P<0.05; **=P<0.01; ***=P<0.001.

Paspalum atratum ‘Ubon’

There was a significant reduction in above ground DM yield in control ($P<0.05$), 10-day single ($P<0.001$) and 20-day single ($P<0.01$) waterlogging treatments (Figure 4a). There also appeared to be a reduction in 10-day cycle and continuous waterlogging treatments, although this was not significant. The DM yield in the control dropped from 12.4 to 5.6 g DM/pot between day 21 and day 84. However, importantly, there was no significant ($P>0.05$) difference between waterlogging treatments at any of the individual harvest dates. The leaf DM results (Figure 4b) reflect those for total above ground DM yield.

Although there was an apparent reduction in mean total live tillers over time, statistically there was only a significant ($P<0.05$) reduction of tillers in the 10-day single waterlogging treatment (Figure 4c). In this treatment, the number of live tillers fell from 11.7 at day 0 to 2.9 at day 84. There was no significant ($P>0.05$) difference between waterlogging treatments at any of the individual harvest dates.

There were significant ($P<0.01$) differences in leaf length over time in all treatments (Figure 4d). In general, there was a 5–15% reduction in leaf length between day 21 and day 84, with the exception of the 10-day single waterlogging treatment which decreased by approximately 40%. There was no significant ($P>0.05$) difference between treatments at any individual harvest date.

Urochloa hybrid ‘Mulato II’

Above ground DM yield significantly ($P<0.05$) decreased over time in all treatments except the 20-day single treatment (Figure 5a). Significant ($P<0.05$) differences were detected between waterlogging treatments at each of the harvest times. The 10-day cycle and continuous waterlogging treatments caused the greatest effect, with above ground DM yield falling to less than 2 g DM/pot by day 84. The leaf DM results (Figure 5b) reflect those for total above ground DM yield.

The reductions in above ground DM yield were reflective of reductions in live tiller number, with significant ($P<0.001$) reductions observed in the 10-day cycle and continuous waterlogging treatments but not in the single waterlogging treatments (Figure 5c). Differences between waterlogging treatments were only significant ($P<0.001$) from harvest day 42 onwards. The total number of live tillers at day 84 were 6.3 and 1.0 for the 10-day cycle and continuous waterlogging treatments respectively.

The effect of the continuous waterlogging treatment is evident, with leaf length falling from 57.1 at day 21 to 12.1 cm at day 84 (Figure 5d). Significant ($P<0.01$) differences between the continuous and other treatments were noticeable from harvest day 42 onwards.

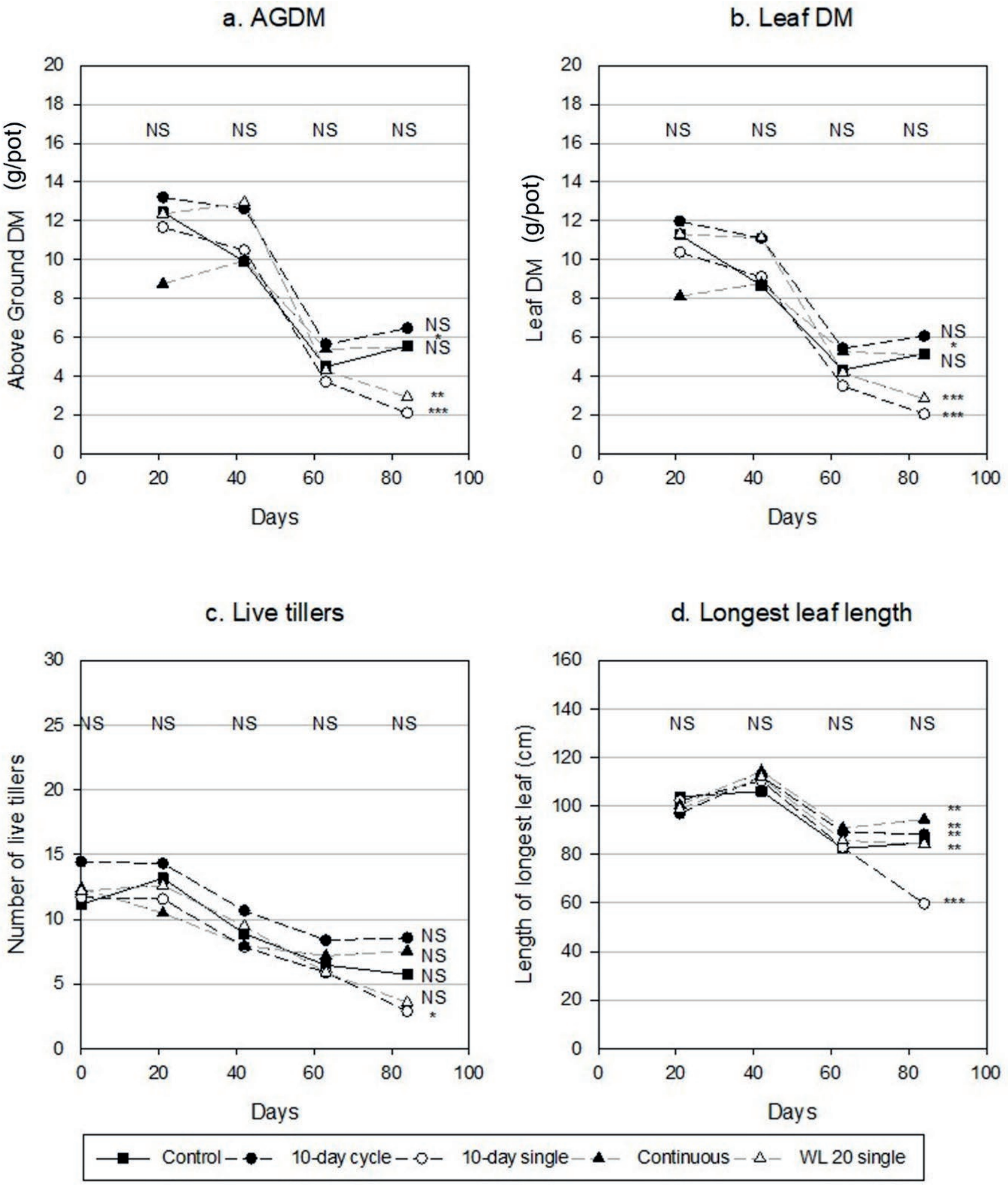

Figure 4. Effects of waterlogging treatments on *Paspalum atratum* (a) above ground DM yield, (b) leaf DM yield, (c) number of live tillers, and (d) length of longest leaf. Waterlogging treatments were Control=nil waterlogging; 10-day cycle=repeated 10 days waterlogging then 10 days control conditions; 10-day single=10 days of waterlogging then control conditions throughout; continuous waterlogging conditions; 20-single=20 days of waterlogging then control conditions throughout. Significant differences between waterlogging treatments at each harvest date (x axis) and change within each waterlogging treatment over time (y axis) are represented by NS=not significant ($P>0.05$); *=$P<0.05$; **=$P<0.01$; ***=$P<0.001$.

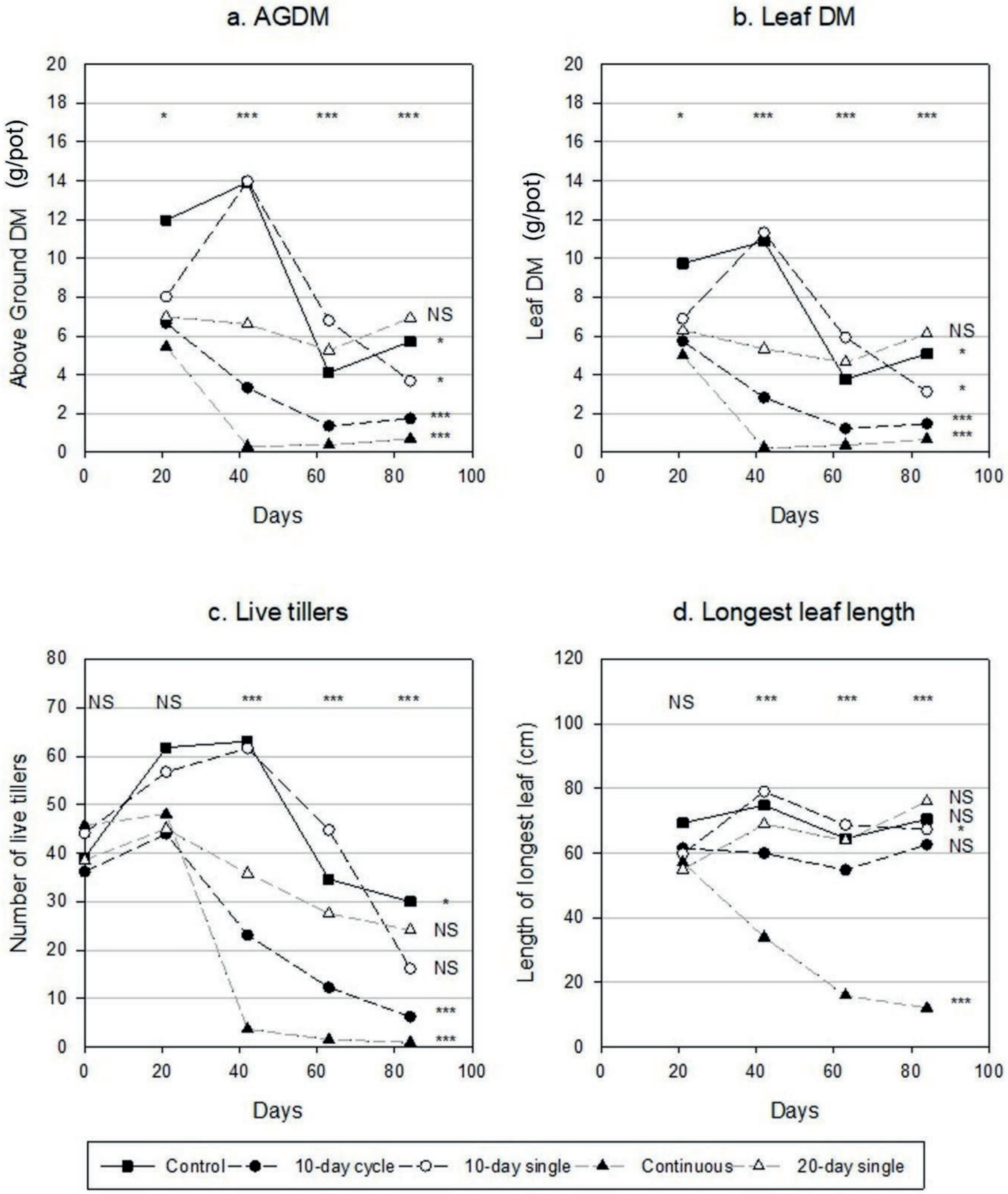

Figure 5. Effects of waterlogging treatments on *Urochloa* Hybrid 'Mulato II' (a) above ground DM yield, (b) leaf DM yield, (c) number of live tillers, and (d) length of longest leaf. Waterlogging treatments were Control=nil waterlogging; 10-day cycle=repeated 10 days waterlogging then 10 days control conditions; 10-day single=10 days of waterlogging then control conditions throughout; continuous waterlogging conditions; 20-single=20 days of waterlogging then control conditions throughout. Significant differences between waterlogging treatments at each harvest date (x axis) and change within each waterlogging treatment over time (y axis) are represented by NS=not significant (P>0.05); *=P<0.05; **=P<0.01; ***=P<0.001.

Urochloa humidicola

The above ground DM yield of *U. humidicola* decreased significantly (P<0.001) over time in all waterlogging treatments (Figure 6a). The DM yield of all waterlogging treatments decreased from >15 g DM/pot at day 21 to <3 g DM/pot by day 84. No significant differences were found between waterlogging treatments from day 42 onwards. The lower above ground dry matter for the 20-day single treatment appears to be due to initial differences between plants that were randomly assigned to the same treatment. The leaf DM results (Figure 6b) reflect those for total above ground DM yield.

Above ground DM yields were reflective of significant (P<0.001) reductions in the number of live tillers (Figure 6c). Total live tillers decreased from >90 at day 0 to <18 by day 84 in all waterlogging treatments. No significant differences were found between waterlogging treatments at any of the measurement days.

Longest leaf length followed the same decreasing trend (Figure 6d), declining significantly (P<0.01) between day 0 and 84 from >80 to <50cm. There was no significant (P>0.05) difference in leaf length between waterlogging treatments at any of the harvest dates.

Urochloa ruziziensis

The amount of above ground DM changed significantly (P<0.001) between harvests for both the 10-day cycle and continuous waterlogging treatments (Figure 7a). The above ground DM yield of the control and single waterlogging treatments did not significantly change over time but were higher than the 10-day cycle and continuous waterlogging treatments at the 42-, 63-, and 84-day harvest times. The leaf DM results (Figure 7b) reflect those for total above ground DM yield.

There was a general decreasing trend in the number of live tillers over the experimental period (Figure 7c), with the exception of the 20-day single waterlogging treatment (P>0.05). Significant (P<0.001) differences between waterlogging treatments were detected at days 42 and 63 only, with the 10-day cycle and continuous waterlogging treatments resulting in less live tillers.

There was no significant (P>0.05) change in the length of the longest leaf throughout the experiment in any of the waterlogging treatments (Figure 7d). There were significant differences in longest leaf length between species at days 42 and 63, with the 10-day cycle and continuous waterlogging treatments tending to result in shorter leaves.

Digitaria eriantha

The amount of above ground dry matter decreased significantly (P<0.05) over time in the control and 10-day single waterlogging treatments, i.e. the treatments representing the least amount of waterlogging (Figure 8a). There was only a significant (P<0.05) difference between waterlogging treatments at the 63-day harvest point. The leaf DM results (Figure 8b) reflect those for total above ground DM yield. Due to the growth characteristics of *D. eriantha*, the number of live tillers and the longest leaf length were not recorded because this was difficult to determine.

Total harvested dry matter

Figure 9 shows the total dry matter harvest from the 4 cuts, not including the first cut before treatments were applied. Under control conditions the only significant difference was between *M. maximus* and *D. eriantha*. Under the 10-day single waterlogging event, all species were higher yielding than *D. eriantha*. Under the 20-day single waterlogging event there was no difference between treatments. Under the 10-day cycle, *P. atratum* and *U. humidicola* were higher yielding than *M. maximus* ‘TD58’, *U. ruziziensis* and *Urochloa* hybrid ‘Mulato II’, with the other species not significantly different. Under continuous waterlogging there was a clear difference between the 4 waterlogging tolerant species, and the 3 less-tolerant species, with ‘Mulato II’ the lowest yielding.

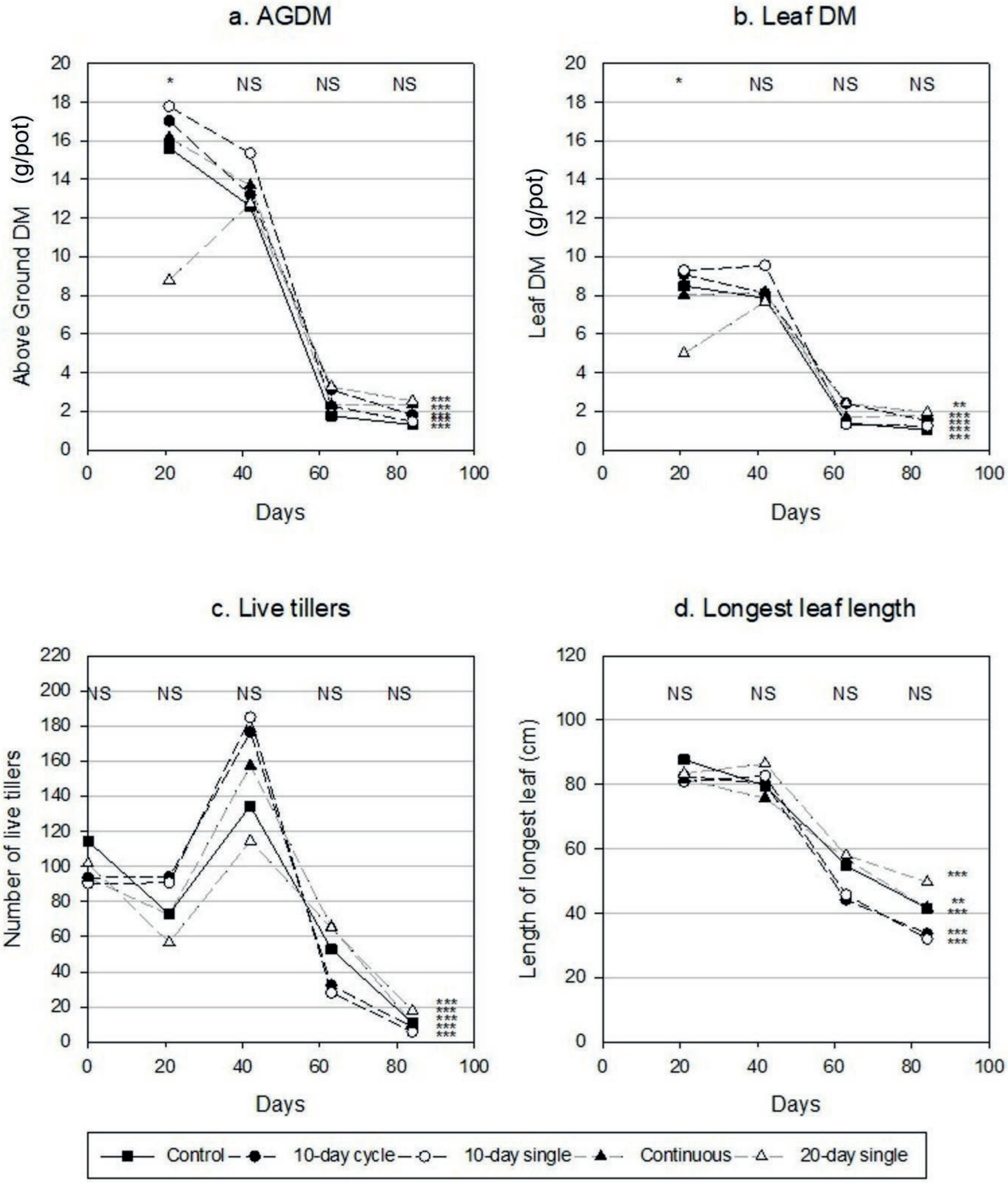

Figure 6. Effects of waterlogging treatments on *Urochloa humidicola* (a) above ground DM yield, (b) leaf DM yield, (c) number of live tillers, and (d) length of longest leaf. Waterlogging treatments were Control=nil waterlogging; 10-day cycle=repeated 10 days waterlogging then 10 days control conditions; 10-day single=10 days of waterlogging then control conditions throughout; continuous waterlogging conditions; 20-single=20 days of waterlogging then control conditions throughout. Significant differences between waterlogging treatments at each harvest date (x axis) and change within each waterlogging treatment over time (y axis) are represented by NS=not significant (P>0.05); *=P<0.05; **=P<0.01; ***=P<0.001.

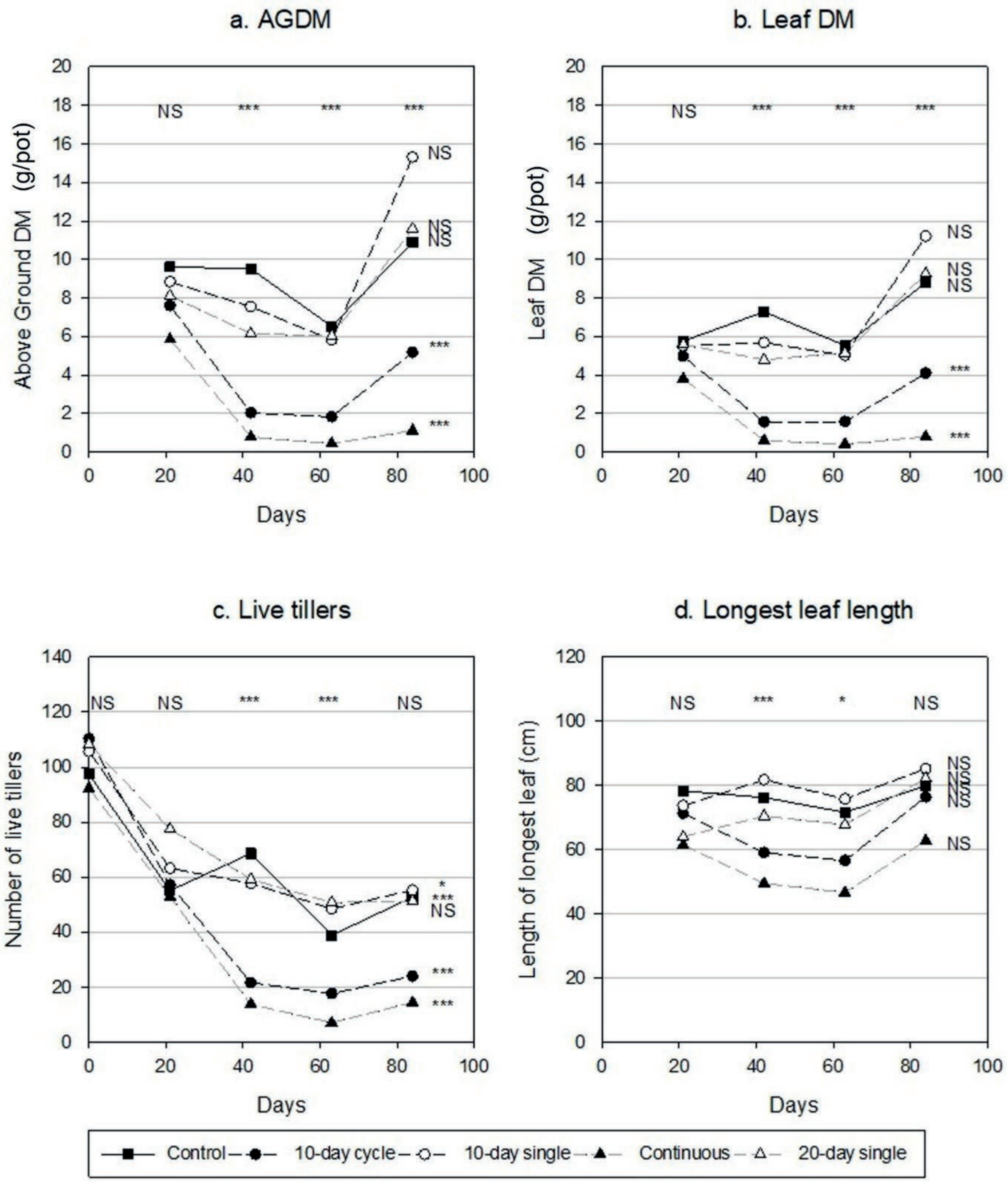

Figure 7. Effects of waterlogging treatments on *Urochloa ruziziensis* (a) above ground DM yield, (b) leaf DM yield, (c) number of live tillers, and (d) length of longest leaf. Waterlogging treatments were Control=nil waterlogging; 10-day cycle=repeated 10 days waterlogging then 10 days control conditions; 10-day single=10 days of waterlogging then control conditions throughout; continuous waterlogging conditions; 20-single=20 days of waterlogging then control conditions throughout. Significant differences between waterlogging treatments at each harvest date (x axis) and change within each waterlogging treatment over time (y axis) are represented by NS=not significant (P>0.05); *=P<0.05; **=P<0.01; ***=P<0.001.

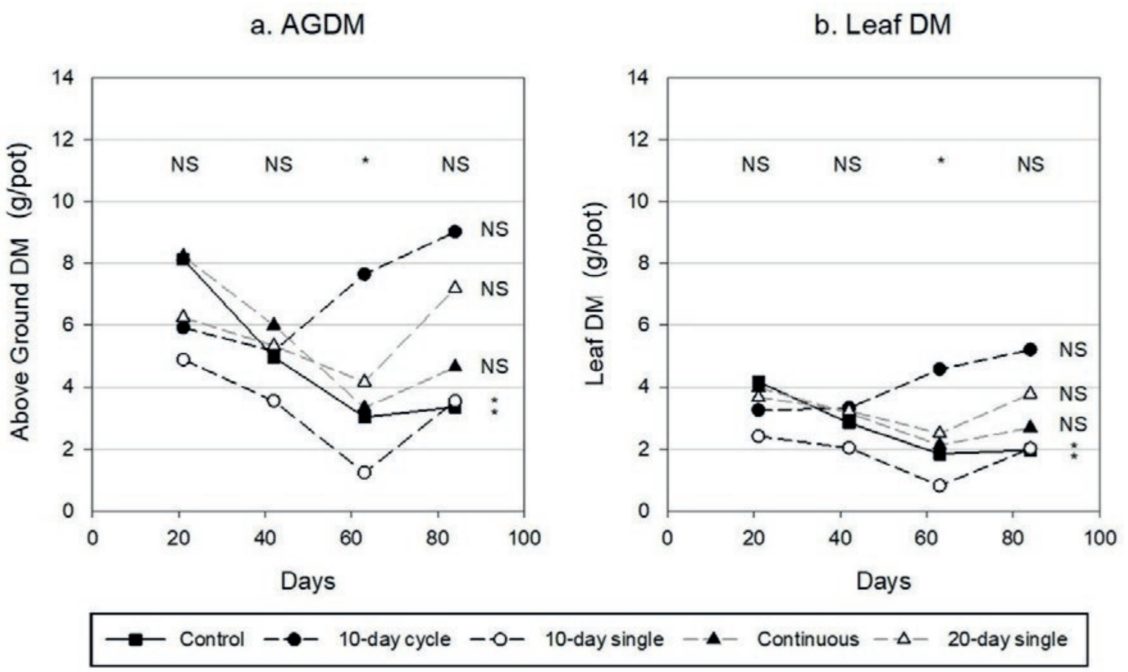

Figure 8. Effects of waterlogging treatments on *Digitaria eriantha* (a) above ground DM yield, (b) leaf DM yield. Waterlogging treatments were Control=nil waterlogging; 10-day cycle=repeated 10 days waterlogging then 10 days control conditions; 10-day single=10 days of waterlogging then control conditions throughout; continuous waterlogging conditions; 20- single=20 days of waterlogging then control conditions throughout. Significant differences between waterlogging treatments at each harvest date (x axis) and change within each waterlogging treatment over time (y axis) are represented by NS=not significant (P>0.05); *=P<0.05; **=P<0.01; ***=P<0.001.

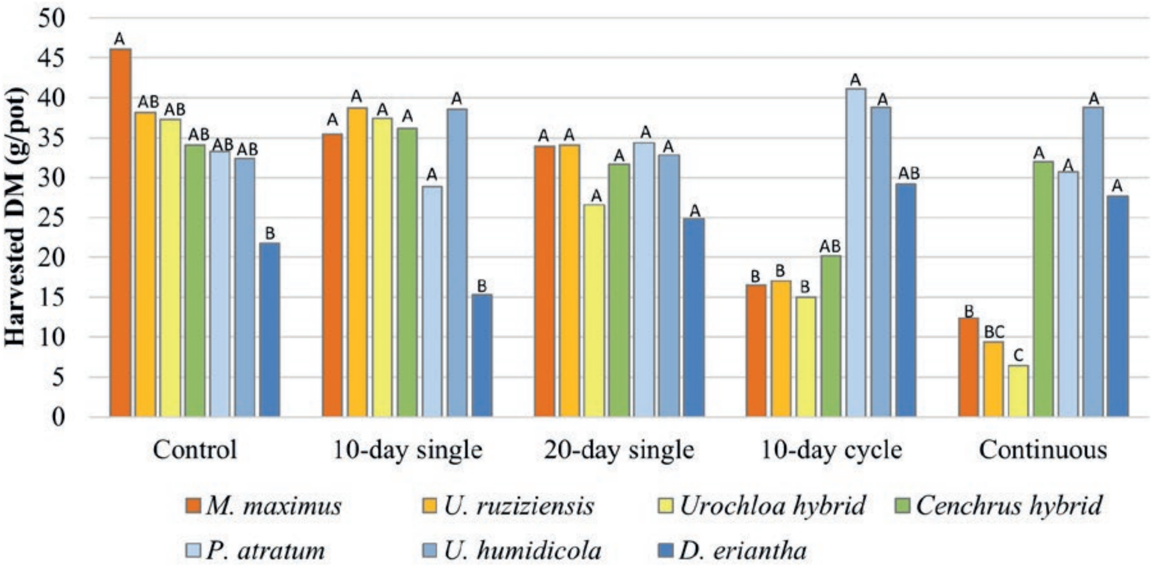

Figure 9. Effect of waterlogging treatments on total above ground DM harvest (4 harvest dates) of *Megathyrsus maximus* 'TD58', *Urochloa ruziziensis*, *Urochloa* hybrid 'Mulato II', *Cenchrus purpureus* × *C. americanus* 'VA06', *Paspalum atratum* 'Ubon', *Urochloa humidicola* and *Digitaria eriantha*. Waterlogging treatments were Control=nil waterlogging; 10-day cycle=repeated 10 days waterlogging then 10 days control conditions; 10-day single=10 days of waterlogging then control conditions throughout; continuous waterlogging conditions; 20-single=20 days of waterlogging then control conditions throughout. Within each waterlogging treatment, species means with the same letter are not significantly (P>0.05) different to each other. Colours for different species reflect typical experience of waterlogging tolerance, with blue colours reflecting waterlogging tolerance, yellow colours reflecting waterlogging susceptibility, and green in-between.

Discussion

The results for the *Urochloa* species support our first hypothesis of which would be the most waterlogging tolerant species. The International Centre for Tropical Agriculture (CIAT) commercialised the *Urochloa* hybrids 'Mulato' and 'Mulato II' but noted that these cultivars are not tolerant of waterlogging (Cardoso et al. 2013). This was confirmed by the results in the current study where repeated waterlogging events reduced the number of live tillers and the above ground dry matter of 'Mulato II' over time. Shoot dry matter (g DM/pot) of 'Mulato II' was also reduced after the third regrowth cycle (80 days) of waterlogging in a study reported by Junior et al. (2016). The number of live tillers was not affected by the single waterlogging event. Thus, 'Mulato II' may persist in areas where short seasonal waterlogging occurs but is not recommended for areas that are waterlogging prone.

Similarly, the number of live tillers, leaf DM and above ground dry matter of *U. ruziziensis* was significantly affected by repeated waterlogging events. This is in agreement with studies by Hare et al. (2004) showing low tolerance of *U. ruziziensis* to waterlogging, with high plant mortality (>50%) and lower plant DM compared with control plants after 20 days. Jiménez et al. (2015a) also noted a reduction in green leaf area and green leaf DM in waterlogged *U. ruziziensis*. In addition, Hare et al. (1999) found that productivity declined on waterlogged soils after the first year of production. The results for 'Mulato II' and *U. ruziziensis* support our second hypothesis that the repeated cycling or continuous of waterlogging is more damaging than the length of time of the waterlogging.

In contrast, there was no difference between the control and waterlogging treatments in *U. humidicola*. This compares with other studies that have also reported that *U. humidicola* has known waterlogging tolerance (Dias-Filho and Carvalho 2000; Cardoso et al. 2013) while Jiménez et al. (2015a) showed *U. humidicola* had greater tolerance than *U. ruziziensis*. The mechanisms for the greater waterlogging tolerance of *B. humidicola* over *U. ruziziensis* were elucidated by Jiménez et al. (2015b) and include greater aerenchyma formation, smaller stele proportions, and increased suberin deposition. These responses under waterlogged conditions increase the flow of oxygen to the roots and reduce the effect of reactive oxygen species in the leaves, which affects the efficiency of photosynthesis (Jiménez et al. 2015b). In addition, under waterlogged conditions *U. humidicola* increases the proportion of lateral roots close to the surface (Cardoso et al. 2014), where oxygen may be more plentiful. We also observed rooted stolons, a high proportion of which were above the waterlogged soil surface, which warrants further study. The reason for the decreasing growth of *U. humidicola* in our experiment is not clear, although the cutting interval may have been too short for plants to recover sufficiently after each cut. The reduced light in the greenhouse may have compounded this effect. As such, further experimentation under field conditions is warranted.

In addition to the existing cultivars with known tolerance for use in waterlogging prone areas, breeding for waterlogging adapted traits is a future research area for *Urochloa*. The *Urochloa* genus is one of the most widely cultivated grasses in tropical systems. CIAT has undertaken screening of *Urochloa* hybrids for waterlogging tolerance with success (Cardoso et al. 2013), which should result in new cultivar releases in the future.

Megathyrsus maximus 'TD58' was able to recover from single waterlogging events as observed with the above ground dry matter, live tillers, leaf length and leaf DM matching the control after day 21. In contrast, production following 10-day cycling and continuous waterlogging treatments was severely affected by a decline in live tillers. This supports our second hypothesis that repeated or continuous waterlogging is more damaging than the length of time of the waterlogging. A similar moderate level of tolerance was also observed by Hare et al. (2004) in *M. maximus* ('Purple panic'), where 20 days of waterlogging stunted plants and reduced plant dry weights. For this reason, *M. maximus* 'TD58' is not suitable for planting in areas where multiple or long-term waterlogging events over a season are expected.

The waterlogging tolerance of *C. purpureus* × *C. americanus* 'VA06' was one of the surprising results of the experiment. However, there was a lot of variability within treatments and the results are inconclusive. The Ba et al. (2014) study did not rank 'VA06' highly for waterlogging tolerance, however the study was only based on a visual rating. In contrast, the authors have observed this cultivar appearing to be healthily growing in inundated fields, when left in an un-cut condition. The mechanisms of waterlogging tolerance of 'VA06' and implications for its management are future areas of research that could have practical implications for such a popular cultivar. Similar to *U. humidicola*, further evaluation under field conditions is required to understand the response to waterlogging or undertaking the experiment again with more replicates.

P. atratum 'Ubon' was one of the most waterlogging tolerant species in studies by Hare et al. (2004), but their studies also showed a decline in dry weight yields the longer the waterlogging period lasted. 'Ubon' was released in Thailand following positive DM evaluation against other species in seasonally waterlogged and seasonally dry soils in northeast Thailand (Hare et al. 1999). In the current study, above ground dry matter yields declined in some treatments over time, but there was no significant difference between waterlogging treatments and control for any of the harvest dates. In addition, the number of live tillers did not change significantly over time and there was also no difference between waterlogging treatments and the control, suggesting that *P. atratum* was also one of the most waterlogging tolerant species in the current study. Beloni et al. (2017) reported variation in responses to waterlogging amongst *Paspalum* genotypes and suggested this could be exploited in further plant breeding.

Numerous factsheets report waterlogging tolerance in *D. eriantha* including Cook et al. (2020), however there are few published studies. This species performed well in experiments by Boschma et al. (2008), although the length of waterlogging was only short. Our studies concur with that general assessment of the species

Conclusions

Our results concur with our original hypothesis that *U. humidicola*, *P. atratum* and *D. eriantha* would be tolerant of waterlogging and that the production of other species would be more affected by waterlogging. Repeated waterlogging events exacerbated the effects on DM production and tiller survival in the less tolerant species *M. maximus*, *Urochloa* hybrid 'Mulato II' and *U. ruziziensis*. These results reinforce current field-based knowledge, though further field-based evaluation may strengthen recommendations.

Understanding of the response of different species and cultivars to waterlogging can help farmers to select appropriate species and cultivars for different locations in the landscape. This knowledge needs to be paired with other information about forages such as suitable soil conditions, production potential and nutritive value. Further studies are required to elucidate best management practices for forages under waterlogging conditions. For example, increasing the cutting height and cutting interval are likely methods for ameliorating some of the effects, to better manage less tolerant forages for persistence through periods of waterlogging. Farmers in the study region have shown a willingness to adopt new forage species, and clear recommendations will help them to manage their forage resources to maintain production and reduce risk.

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