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Effects of Root-trimming and Cutting-heights on Growth Performance of Potted Native Warm-season Grasses

Vitalis W. Temu[1], David Johnson[1] & Maru K. Kering[1]

[1] Agricultural Research Station, Virginia State University, Petersburg, Virginia, USA

Correspondence: Vitalis W. Temu, Agricultural Research Station, Virginia State University, 238 M.T. Carter Bldg, P.O. Box 9061 Petersburg, Virginia, USA. Tel: 1-804-524-6717. E-mail: vtemu@vsu.edu

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Abstract

Mechanized transplanting of native warm-season grass (NWSG) seedlings raised in biodegradable strip-cups may require trimming outgrown and entwined roots to facilitate individual placement and complete root covering. During establishment, mowing is often used to reduce weed competition and promote tillering. In two randomized complete block split-split-plot design experiments, effects of root-trimming and cutting-height on growth and biomass production of potted NWSGs [big bluestem (BB, *Andropogon gerardii* Vitman), eastern gamagrass (GG, *Tripsacum dactyloides* L.), indiangrass (IG, *Sorghastrum nutans* L.), and switchgrass (SG, *Panicum virgatum* L.)] were assessed. Six-week old seedlings were transplanted, with or without root-trimming, and four of each type and species, assigned to 10-, 15-, or 20-cm cutting-height. All plants were fertilized uniformly and watered sufficiently. After a 7-d adjustment period, plants were clipped to 10 cm which promoted tillering. A three-week regrowth was then allowed before the first of three forage harvests, at assigned cutting-heights. Plant heights were recorded every two weeks after transplanting and on each harvest date. Data were analyzed for effects of root-trimming, cutting-height, and species. Root-trimming had no effect on the parameters. Cutting-height had no effect on plant heights except for second GG and SG regrowths, and/or the third BB and SG. Cutting-height affected only SG forage biomass significantly ($P < 0.05$) during year1 and every species during year2 with 100%+ greater values at the 20- than the 10-cm. All 20-cm average growth rates and belowground biomass in year2 were greater ($P < 0.001$) than the 10-cm by > 100%, but with similar root:total biomass ratios. Overall, species yield increased in the order; IG<BB<GG<SG. With adequate soil moisture and fertility, results indicate that root-trimming may not affect growth or forage biomass of NWSGs during establishment. Mowing NWSGs, during establishment, for up to three 20-cm cuts at ≥ 3-week intervals, may not impact recovery growth or belowground biomass, negatively. Results from field studies are required ahead of practical establishment management recommendations.

Keywords: native grass, crown, transplant, seedling, root-trimming cutting-heights, yield, growth rate

1. Introduction

1.1 Establishment Methods

Establishing NWSG stands from seeds is difficult due to a number of factors including poor germination, improper seeding depths and weed competition (Springer, 2005). Low seedling vigor makes them unable to compete with weeds for resources with low moisture and droughty conditions being frequently responsible for establishment failure (Blake, 1935). Following successful germination and seedling emergency, it usually takes at least two years for NWSG stands to be harvest-ready, and even longer if reseeding of failed patches is involved (Miller & Dickerson, 1999; Temu et al., 2016). Slow development of extensive root systems during early establishment phase is known to be responsible for delayed vegetative growth of NWSGs (Miller & Dickerson, 1999). It is reported that, rapid establishment of adventitious roots is essential for seedling survival (Hyde et al., 1971). Even with effective weed control, the window of favorable growth that ensures availability of sufficient root biomass towards fall is significantly reduced. During this phase, resources are preferentially channeled to initiation of dormant tiller buds and energy reserves for the next spring rather than current vegetative growth. As a result, significant vegetative growth of new NWSG stands can only occur in the next growing season after germination.

As an alternative establishment approach, NWSG seedlings can be raised in a modified environment and be ready for transplanting as soon as field temperatures become favorable for growth. Use of transplants give the NWSGs a growing advantage over weeds at stand establishment, which enables them to finish their first growing season with energy-rich crowns and many dormant tillers for a robust spring growth (Temu, et al., 2016). However, the effectiveness of transplanting in NWSG establishment may depend on factors like seedling age, root biomass, root-covering at planting, soil moisture availability, weed challenges, and early defoliation management as well as their interactions. Therefore, decisions on the appropriate timing and frequency of specific management practices, including harvesting, should take into account possible impacts of the individual factors and/or their interaction effects.

1.2 Transplants and Defoliation Management

When planting is delayed in anticipation of favorable growing conditions, seedlings in biodegradable strip-cups may have their roots outgrow and entwine as to impact mechanized planting operations. Such outgrown and entwined roots may have to be trimmed in order to facilitate individual placement and achieve complete root covering. Information on how root-trimming affects seedling growth and establishment success is scarce and not many studies have been done on it. In the case of GG, for example, root-trimming has been found to result in reduced shoot growth (Roden et al., 2002). However, information about root-trimmed seedlings of other NWSGs remains scarce or non-existent.

Similarly, while strategic mowing during establishment is intended to control weeds and increase the NWSG tiller densities (Meyer et al., 1999), negative impacts on growth and yield can occur if not done appropriately. To ensure a quick recovery, cutting-heights should be high enough to leave sufficient leaf area and minimize loss of growing points. Furthermore, defoliation should not be too intense during the establishment year when the plants are short of energy reserves for recovery growth. Therefore, to avoid undesirable consequences, decisions on defoliation management are usually based on anticipated changes in re-growth rates and subsequent biomass production. However, species differences in leaf morphology and tiller orientation may influence their response to similar defoliation treatments. Information on how the growth of NWSG transplants could be affected by combined root-trimming and the intensity of early defoliation is an important tool for designing appropriate establishment management strategies. Therefore, this study assessed the effects of root-trimming at planting and three cutting-heights on growth rates and forage yields of four potted NWSG species.

2. Materials and Methods

2.1 Study Location and Experimental Layout

The study was conducted in a well ventilated (open-walls) high tunnel at Virginia State University's research farm (Randolph Farm) located in Chesterfield county, Virginia at 37° 13'' 43' N; 77° 26'' 22' W, and 45 m above sea level. The area has a 20-year average June, July, and August day temperatures of 30.2, 32.1, and 31.2 ^{o}C, respectively (Satellite N.O.A.A., 2013). In two successive years, the experiments were ran in a randomized complete block design with a split-split-plot treatment allocation for effects of root-trimming (main-plot factor), species (sub-plot factor), and cutting-height (sub-sub-plot factor).

Degradable strip-cups, 2 × 2 cm top and 2 cm deep, filled with germination pot media (Premier ProMix Germinating Mix 3.8CF PGX, Griffins Greenhouse supplies, Richmond, VA) were arranged on perforated flat trays and seeded with BB, GG, IG, and SG. Seeded trays were placed on greenhouse tables covered with a plastic sheet and kept moist by bottom-up watering. After six weeks of growth in the high tunnel, 24 seedlings of each species were transplanted into plastic greenhouse pots (28 cm-top, 20 cm-bottom, and 30 cm-deep) filled with the same pot medium. At transplanting, 12 seedlings had their outgrown roots trimmed with a matching set of 12 left intact. All potted plants received the same fertilizer treatment and were watered as needed to ensure sufficient moisture throughout the experimental periods. All potted plants were allowed a 7-d long initial growth period, so they could adjust to the new environmental conditions and recover from stresses associated with transplanting. After the adjustment period, the 12 root-trimmed and 12 intact plants of each species were randomly assigned to 10-, 15-, or 20-cm cutting-heights (treatments) and thus replicating each treatment four times. All plants were then clipped at 10-cm height, to promote tillering, and allowed a 30-d long regrowth before the first forage harvest. The pre-treatment clipped biomass was insignificant and, therefore, discarded. For each species, the set of 24 pots was arranged on a separate table (2.4-m L × 1.2-m W). Similarly, a second year trial was set, but with longer respective regrowth periods (23-, 25-, and 40-d) to the first, second, and third harvests, respectively. At the same cutting-heights, increasing the regrowth period was considered necessary to allow significant recovery and substantial biomass production.

2.2 Measurements and Data Collection

2.2.1 Aboveground Measurements

During the 30-d long first re-growth in the first year, two bi-weekly plant leaf height (LH) measurements as vertical distance from the exposed pot media (synonymous with ground surface) to the top bending point of most leaves were recorded on four random tillers per pot between 9:00 and 10:00 am. After the second bi-weekly height measurement, plants were clipped as assigned and first re-growth forage biomass determined. For each potted plant, the clipped material was weighed before and after oven-drying (at 65 ^{o}C) to constant weight. Similarly, subsequent LH measurements as well as the second (15-d) and third (17-d) re-growth shoot biomass were obtained to assess yield response to root-trimming and cutting-height treatments. During the second year, growth and yield data were collected and processed similarly. However, due to unexplained lack of treatment differences in the recorded year1 plant heights, LH measurements were considered potentially unreliable and excluded from the second year data set.

To assess how the treatments might affect plant response to defoliation, the average growth rate (AGR) on the basis of mean shoot biomass production was calculated as [AGR = DW/number of days between successive cuts]. To correct for differences in reserve carbohydrates immediately before the preceding harvest on the rate of recovery growth, the calculated AGR values were expressed as proportions of their preceding harvested DWs to get the respective relative growth rates (RGR). In doing so, the first and second harvest yields were regarded as indicators of the plant sizes that produced the respective second and third harvest weights. Thus [RGR2 = (AGR2/DW1)*100] and [RGR3 = (AGR3/DW2)*100].

2.2.2 Belowground Biomass

After the final harvest, during the second year, each pot was repeatedly watered with a garden shower head then emptied into a 40-L plastic container in which the contents were gently moved up and down to free the loosely held potting media. Then the semi-cleaned root-crown mass was repeatedly flushed with the shower head over a wire mesh that trapped any roots breaking loose. The roots were trimmed off the crown and separately oven-dried to constant weight after which the dry weights were recorded. For each pot, the root and crown dry weights were added to the cumulative forage weight to get total (above- and belowground) biomass. The root weight was then divided by the total biomass to get the respective root:total biomass (RTB) ratio and used for establishing changes in allometric relationships.

2.2.3 Statistical Analyses

The data were analyzed using a computer-based statistical software, the proc GLM, SAS 9.4, Copyright (c) 2002-2014 by SAS Institute Inc., Cary, NC, USA. During the statistical analyses, individual harvest weights for each treatment, within species, were combined as total forage biomass. Respective treatment means were compared within and between species. Means separation was according to Fishers LSD at $\alpha = 0.05$.

3. Results and Discussion

For convenience, the results on measured and derived forage biomass responses to treatment from year1&2 data sets are discussed in separate subsections. Root-trimming had no effect on all parameters determined (Table 1) and was, therefore, omitted from subsequent analyses. Also, due to significant species*cutting-height interactions, results are reported separately for cutting-heights within species and the *vice versa*.

3.1 Effects of Root-Trimming on Growth

The observed lack of root-trimming effect on plant heights and forage DM yield suggests that the root loss imposed was probably not severe enough to impact shoot growth. In fact, in the case of GG, a < 50% loss of root mass is known to have no impact on subsequent shoot growth (Roden et al., 2000). It is likely that the uniform watering and fertilizer application adopted in the current study helped to mask differences, if any, associated with the root biomass at planting. Because root-trimming had no effect on all parameters determined, as shown in the summary of ANOVA for total forage biomass (Table 1), only effects of cutting-height and species are discussed.

3.1.1 Plant Regrowth Heights

As summarized in Table 2, and for each species, the first year plant heights recorded during the first 30-d regrowth showed no treatment difference. However, following the first forage harvest, regrowths in GG and SG were taller for the 20-cm than 10-cm (Table 2). For the second regrowth, SG and BB cut at 20-cm had taller plants than those cut at 10-cm height. For each harvest, regrowth heights in IG were similar for all cutting-heights.

Table 1. Summary of analysis of variance for effects of root-trimming (Root loss), Cutting-height (Cut-height), and species on cumulative forage biomass of potted big bluestem, gamagrass, indiangrass, and switchgrass recorded during the first (Year1) and second (Year2) experiments

Source of variation	First year				Second year		
	DF	SS	F Value	Pr > F	SS	F Value	Pr > F
Model	41	7238.5	4.97	<.0001	41566.55	32.99	<.0001
Rep	3	11.99	0.11	0.9524	18.26	0.2	0.8972
Root loss	1	24.29	0.68	0.4121	3.88	0.13	0.7237
Rep*Root loss	3	90.37	0.85	0.474	46	0.5	0.6845
Cut height	2	174.39	6.3	0.0135	11692.64	190.26	<.0001
Root loss*Cut-height	2	38.6	0.54	0.5842	78.52	1.28	0.287
Rep*Root loss*Cut-height	12	166.14	0.39	0.9617	175.8	0.48	0.9197
Species	3	5117.36	47.99	<.0001	27238.75	295.49	<.0001
Species*Root loss	3	65.3	0.61	0.6099	27.73	0.3	0.8246
Species*Cut-height	6	312.27	1.46	0.208	2188.58	11.87	<.0001
Species*Root loss*Cut-height	6	98.39	0.46	0.8338	96.39	0.52	0.7885
Error	54	1919.48	-	-	1659.28	-	-
Corrected Total	95	9157.99	-	-	43225.84	-	-

The first year data set was from potted plants harvested at 30-, 15-, and 17-d intervals while the corresponding second year data set was of plants harvested at 23-, 25-, and 40-d intervals, respectively, but at same heights.

Table 2. Growth response of potted big bluestem, gamagrass, indiangrass, and switchgrass to cutting-heights (cm) in an open-sided high tunnel based on bi-weekly mean plant height[†] measurements between August and September, inclusively

Cut-height (cm)	Species plant-heights			
	Initial 30-d growth[‡]		Bi-weekly regrowth	
	1st 15-d	2nd 15-d	First	Second
	--------cm--------			
--------Big bluestem--------				
10	11.3	15.4	20.5	11.4b[‡‡]
15	10.9	14.3	19.8	13.0b
20	10.9	16.0	25.3	15.7a
Pr > α[§]	0.77	0.15	0.17	<0.001
--------Gamagrass--------				
10	12.8	20.9	16.0b	17.1
15	11.8	19.5	16.9b	17.9
20	13.2	21.6	19.9a	19.9
Pr > α	0.33	0.50	0.02	0.06
--------Indiangrass--------				
10	13.6	15.1	20.0	11.0
15	12.6	14.3	17.9	11.5
20	13.5	15.3	19.0	12.5
Pr > α	0.49	0.44	0.67	0.31
--------Switchgrass--------				
10	10.2	14.9	16.8b	16.4b
15	11.4	16.1	26.9a	17.4ab
20	11.0	16.3	29.1a	19.1a
Pr > α	0.22	0.07	<.001	0.035

[†]Plant heights recorded as vertical distance from the port surface to the bending of topmost leaf blades (three pot^{-1}). [‡]Unlike all other, there was no harvest event preceding the second bi-weekly height measurements; [‡‡]Means of the same species within a column followed by the same letter are not significantly different at α = .05. [§]The probability of difference between means of the same species within column.

3.2 Effects of Cutting-Heights on Subsequent Growth Performance

3.2.1 Forage Biomass

From the year1 data set, species-wise results of forage biomass pot^{-1} are summarized in Table 3. At the 30-d long first harvest, the GG and SG forage biomass showed no treatment difference but the matching values for BB and IG were consistently greater for the 10-cm than the 15- and 20-cm cut heights (Table 3). At the second regrowth harvest, only SG showed treatment differences with 20-cm cutting-height producing significantly (P=0.05) greater biomass (14.4 g DM pot^{-1}) than the other cutting-heights. At the third regrowth harvest, SG and GG cut at 20-cm height produced significantly greater biomass than that cut at 10-cm for both species. While total forage biomass for all species portrayed an upward trend as the cutting-heights increased, it is only in SG that the 20-cm cutting-height produced a significantly greater biomass (29 g pot $^{-1}$) compared to the 10-cm treatment. The observed SG total forage biomass values were 9-units greater for the 20-cm (29 g) than the 10-cm, but similar to that for the 15-cm (25 g) harvest-height.

Table 3. Effects of cutting-heights (cm) on initial 30-d and subsequent bi-weekly regrowth forage yields and growth rates of potted big bluestem, gamagrass, indiangrass, and switchgrass in an open-sided high tunnel between August and September, inclusively, during the first year

Height (cm)	Regrowth dry matter yield				Average growth rate†			Relative growth rate‡	
	Cut1‡‡	Cut2	Cut3	Total	Cut1	Cut2	Cut3	Cut2	Cut3
	--------------g pot^{-1}---------------				-----------mg d^{-1} pot^{-1}-----------			----- mg g^{-1} d^{-1} -----	
---------------Big bluestem---------------									
10	6.1a^{AB§}	6.5^{BC}	5.6^{B}	18^{B}	204a^{AB}	433^{BC}	331^{B}	75c^{B}	58^{AB}
15	3.1b^{BC}	7.0^{C}	5.6^{B}	16^{C}	104b^{BC}	467^{C}	331^{B}	176b^{AB}	49^{A}
20	3.0b^{CB}	7.0^{B}	6.7^{B}	17^{C}	100b^{BC}	467^{B}	397^{B}	194a^{B}	60^{A}
Pr > α¶	<0.001	0.79	0.51	0.36	<0.001	0.79	0.51	0.05	0.66
---------------Gamagrass---------------									
10	8.5^{A}	10.5^{A}	9.6b^{A}	29^{A}	283^{A}	700^{A}	566b^{A}	87b^{B}	63^{A}
15	7.6^{A}	13.1^{A}	10.4ab^{A}	31^{A}	254^{A}	875^{A}	610ab^{A}	124a^{B}	47^{A}
20	7.7^{A}	13.5^{A}	12.9a^{A}	34^{A}	258^{A}	900^{A}	757a^{A}	124a^{B}	57^{A}
Pr > α	0.88	0.38	0.05	0.42	0.88	0.38	0.05	<0.038	0.52
---------------Indiangrass---------------									
10	3.1a^{C}	4.5^{C}	3.1^{C}	11^{C}	104a^{C}	300^{C}	184^{C}	112^{AB}	41^{AB}
15	1.6b^{C}	3.9^{D}	3.5^{C}	9^{D}	54b^{C}	258^{D}	206^{C}	196^{AB}	64^{A}
20	1.9b^{C}	4.2^{C}	4.0^{C}	10^{D}	62b^{C}	283^{C}	235^{C}	173^{B}	56^{A}
Pr > α	0.04	0.69	0.54	0.53	0.04	0.69	0.54	0.15	0.48
---------------Switchgrass---------------									
10	5.0^{BC}	9.5b^{AB}	6.2b^{B}	21b^{B}	167^{BC}	633c^{AB}	368b^{B}	137b^{A}	39^{B}
15	4.2^{B}	11.4b^{B}	9.6a^{A}	25ab^{B}	141^{B}	758b^{B}	566a^{A}	218ab^{A}	51^{A}
20	4.0^{B}	14.4a^{A}	11.0a^{A}	29a^{B}	133^{B}	958a^{A}	647a^{A}	302a^{A}	45^{A}
Pr > α	0.62	<0.001	<0.01	<0.01	0.62	<0.001	<0.01	0.02	0.23

†Average increase in forage dry matter (DM) day^{-1}. ‡Increase in forage DM day^{-1} g^{-1}of the respective preceding harvest weight. ‡‡Numbers 1-3 indicate order of three sequential harvests following a 30-, 15-, and 17-d long regrowth period, respectively. §Within a column, means of the same species followed by the same lowercase letter or the same cut height across species followed by the same uppercase letter are not significantly different at α = .05. ¶The probability of difference between means of the same species within the column.

During the second year, all species had consistently greater forage yields (P <.001) for the 20-cm treatment than the other two (Table 4). Consistently also, forage biomass values were the least for the corresponding 10-cm treatment although not significantly different from the 15-cm ones for the second and third BB harvests or the second of GG (P > .05). For each species, however, cumulative forage biomass was significantly greater for the 20- and least for 10-cm treatment (P < .001). In fact, in all species, the 20-cm cutting-height produced >100% more forage DM than its 10-cm counterpart. The treatment differences in forage biomass were actually consistent with reported negative effects of severe defoliation on plant growth (Ferraro & Oesterheld, 2002). Usually, severely defoliated plants suffer irreversible tissue damages that eventually reflect in reduced subsequent yields. In fact, multiple defoliations have been found to reduce subsequent herbage biomass of warm-season grasses by over 60% (Mullahey, 1990; Forwood & Magai, 1992). This is so because proportions of photosynthetic tissue retained on defoliated plants usually influence how quickly they repair their damaged tissues (Oesterheld & McNaughton, 1991; Lee et al., 2000; Ferraro & Oesterheld, 2002). With severe defoliation, plants lack sufficient residual leaves to supply enough carbon for maintenance and regrowth. They remain in "negative carbon", consuming stored resources until their photosynthetic leaf areas are sufficiently restored (Richards, 1993).

The noted year differences in response to treatment clearly demonstrate the importance of sufficient recovery growth before plants experience subsequent defoliations. That allows the defoliated plants to restore their carbohydrate reserves, which usually influence stand persistence (Slepetys, 2008). During the first year of the current study, recovery growths towards the second and third harvests lasted only about two weeks, while, during the second year, the first and second regrowths took approximately three weeks and nearly five for the third. Based on the current results, three weeks recovery period seemed long enough for NWSG plants cut at 20 cm to effectively restore their photosynthetic capacities, provided soil moisture and nutrient supplies are not limiting.

Table 4. Effects of cutting-heights (cm) on mean forage productivity, belowground biomass, and root:total biomass (RTB) ratio of potted big bluestem, gamagrass, indiangrass, and switchgrass in an open-sided high tunnel from three consecutive harvests (Cut1-3) between mid-July and October

Height (cm)	Regrowth forage yield and growth rate							Belowground biomass				
	Forage yield				AGR†			RGR‡		Root & Crown		Ratio§
	Cut1‡‡	Cut2	Cut3	Total	Cut1	Cut2	Cut3	Cut2	Cut3	Crown	Root	RTB
	g DM pot^{-1}				mg d^{-1} pot^{-1}			mg g^{-1}d^{-1}		g pot^{-1}		
	Big bluestem											
10	4.5c^{BC¶}	2.6b^{C}	0.6b^{B}	7.71c^{C}	197c^{BC}	104b^{C}	14b^{B}	24^{C}	5^{C}	14.6c^{B}	9.9c^{B}	0.30^{A}
15	8.4b^{B}	4.2b^{C}	1.2b^{B}	13.7b^{C}	365b^{B}	167b^{C}	29b^{B}	21^{C}	7^{C}	24.5b^{C}	17.2b^{B}	0.31^{A}
20	14.5a^{B¶}	8.5a^{C}	2.7a^{B}	25.7a^{C}	629a^{B}	340a^{C}	68a^{B}	24^{C}	8^{C}	37.9a^{C}	28.4a^{B}	0.30^{A}
	Gamagrass											
10	5.6c^{B}	10.8b^{B}	8.6c^{A}	25.0c^{B}	242c^{B}	430b^{B}	216c^{A}	87^{A}	21^{A}	33.1b^{A}	11.5b^{B}	0.16^{C}
15	9.6b^{B}	14.6b^{B}	13.2b^{A}	37.5b^{B}	419b^{B}	585b^{B}	331b^{A}	64^{A}	24^{A}	41.5b^{B}	11.5b^{C}	0.13^{D}
20	15.6a^{B}	22.5a^{B}	18.7a^{A}	56.9a^{B}	680a^{B}	900a^{B}	469a^{A}	60^{A}	22^{A}	67.4a^{B}	17.7a^{C}	0.12^{D}
	Indiangrass											
10	2.6c^{C}	2.7c^{C}	1.2c^{B}	6.5c^{C}	114c^{C}	107c^{C}	30c^{B}	49^{B}	12^{B}	4.6c^{C}	2.6c^{C}	0.18^{C}
15	5.6b^{C}	5.4b^{C}	2.7b^{B}	13.7b^{C}	243b^{C}	217b^{C}	69b^{B}	40^{B}	13^{B}	9.75b^{D}	5.5b^{D}	0.18^{C}
20	8.6a^{C}	8.2a^{C}	4.1a^{B}	21.0a^{C}	376a^{C}	328a^{C}	102a^{B}	40^{B}	13^{B}	17.0a^{D}	9.4a^{D}	0.20^{C}
	Swichgrass											
10	11.1c^{A}	13.6c^{A}	7.5c^{A}	32.3c^{A}	483c^{A}	546c^{A}	187c^{A}	54a*^{B}	14^{B}	32.5c^{A}	19.5c^{A}	0.23^{B}
15	20.3b^{A}	20.7b^{A}	12.7b^{A}	53.8b^{A}	884b^{A}	829b^{A}	319b^{A}	41b^{B}	16^{B}	50.0b^{A}	30.2b^{A}	0.22^{B}
20	29.1a^{A}	28.7a^{A}	17.9a^{A}	75.7a^{A}	1267a^{A}	1150a^{A}	447a^{A}	41b^{B}	16^{B}	77.7a^{A}	49.9a^{A}	0.24^{B}
Pr > α#	<.001	<.001	<.001	<.001	<.001	<.001	<.001	>.1	>.1	<.001	<.001	>.1

†Average Increase in forage dry matter (DM) day^{-1}. ‡Increase in forage DM day^{-1} g^{-1} of the respective preceding harvest weight. ‡‡The number indicates the order in three sequential harvests following a 23-, 25-, and 40-d long regrowth period, respectively. §A ratio obtained by dividing the recovered root mass by the combined above- and belowground biomass (RTB). ¶Within a column, means of the same species followed by the same lowercase letter or the same cut height across species followed by the same uppercase letter are not significantly different at α = .05. *For switchgrass only, treatment means differed significantly (P = .03). #The probability of difference between means of the same species within a column.

3.2.2 Daily Weight Gains and Relative Growth Rate

With respect to forage production, management decisions on appropriate harvest regimes are better based on the rate at which plants may recover from defoliation events. In the current study, the year1 AGRs, based on estimated daily weight gains (mg d^{-1}), showed that regrowth rates following the first (30-d) harvest were faster for the 10-cm than the 15- and 20-cm, for BB (204 mg d^{-1}) and IG (104 mg d^{-1}) (Table 3). The corresponding GG or SG values were not statistically different and averaged 265 and 147 mg d^{-1}, respectively. Towards the second harvest events, only SG exhibited treatment differences in AGRs, with mean daily gain for the 20-cm cutting-height (958 mg d^{-1}) being greater than for the 15- and 10-cm cutting-heights. Towards the third harvest, however, AGR for the 20-cm cut SG (662 mg d^{-1}) was 258 units faster than for the 10-cm, but statistically similar to the 15-cm one. Again, on the second year data, all species showed clear and consistent treatment differences in AGR (Table 4) with greater ($P < 0.001$) values for the 20-cm, than the 15-cm, and 10-cm cutting-heights, respectively.

Exceptions were BB towards the second and third harvests and GG towards the second harvest. Generally, AGRs for plants in the 20-cm were over 100% greater than those for 10-cm cutting-height. These results are consistent with the assertion that negative effects of severe defoliation on recovery growth are influenced by the proportions of their residual photosynthetic tissues (Crider, 1955; Ferraro & Oesterheld, 2002). Overall, plants tended to regrow faster towards the second harvest than their respective first and third harvests.

On hay fields, differences in pre-harvest energy reserves and stand vigor will influence the rates at which subsequent harvests could be realized. So, to appropriately assess response to defoliation, it is important that likely influence of initial plant size on recovery growth and/yield performance of defoliated grasses is also considered. In this section, therefore, possible effects of the pre-harvest plant sizes on regrowth yields calculated as daily forage biomass production per gram of the preceding harvest weights, as RGR estimates, are discussed.

The statistical analysis results on the respective RGR values for the second and third harvests are presented in Table 3. There was an increase in RGR for higher cutting-heights towards the second harvest, during year1. This increase in RGR was significant in all species except IG. However, towards the third harvest, RGR differences between cutting-heights, in year1, were only numerical. During the second year, RGR values towards the second harvest for BB, GG, and IG or the third for each species (Table 4) showed no treatment difference ($P > 0.1$). The fact that even for SG only one treatment differed from the rest ($P = 0.03$) and that this higher RGR value for the 10-cm was inconsistent with its forage biomass ranking makes it an isolated outlier. The observed declines in AGR and forage biomass with low cutting-heights clearly demonstrated the practical significance of appropriate harvest management in NWSG stands. Cutting NWSGs too low causes severe loss of growing points, thus leaving recovery more dependent on new sets of leaves (Briske 1986) and subsequently reduce forage biomass. At the same harvest frequency, plants cut too low take longer to re-establish sufficient photosynthetic leaf area and will, therefore, have relatively lower cumulative yields. So, the observed consistent treatment differences in derived yield responses, during the second year, are attributable to the longer recovery periods allowed.

3.2.3 Belowground Biomass

Cutting-height had significant effects ($P < 0.05$) on both root and crown weights (Table 4). In all species, the crown and root biomass produced for the 20-cm cutting-height were greater than for the other cutting-heights. In fact, it exceeded that for the 10-cm cutting-height by over 50%. It is only in GG that the differences between the 15-cm and 10-cm cutting-heights were not significant ($P > 0.05$). Over all, the magnitudes of the decrease in root and crown biomass were consistent with the severity of defoliation associated with the cutting-heights. The observed decline in belowground biomass weight agrees with reported negative impacts of multiple defoliations on root weight and their nonstructural carbohydrates content in grasses (Christiansen and Svejcar, 1987; Engel et al,. 1998). In fact, immediately following defoliation, grasses usually experience a stoppage in root growth that reflects the percentage of foliage removed and continues until recovery of the top growth is advanced (Crider, 1955). For example, in most C_3 and C_4 grasses, root growth ceases immediately following a ≥ 50% leaf area removal (Richards, 1993; Turner et al., 1993). For shorter cutting-heights and/or harvest frequencies, therefore, reduction in respective root and crown biomass is expected, an observation also made in the current study. This is so because of preferential resource allocation to aboveground growth at the expense of roots, a scenario usually exhibited by plants recovering from defoliation (Richards, 1984; Turner et al., 1993; Turner et al., 2007).

The demonstrated decrease in crown and root biomass for the shorter cutting-heights has implications on how long a recovery growth should be allowed before plants can be considered ready for the next harvest. Subsequent defoliations that do not allow enough time for recovery may cause progressive decline in growth performance due to weakening of the plants, which may favor the growth of undesirables. Crown size is important as it is the origin of the adventitious roots, the main rooting system in warm-season grasses (Meltcalfe & Nelson, 1985). All species showed no effect of cutting-height in their derived RTB ratios, implying that defoliation affected the below and aboveground biomass production in similar proportions.

3.3 Species Response to Cutting-Heights

3.3.1 Species Forage Biomass

In the current study, the forage biomass means showed significant species differences (Table 3). During the first year, and for each cutting-height, IG had the least ($P < 0.001$) forage values at each harvest, as well as total biomass while GG generally had the greatest forage weight. For 15- and 20-cm cutting-heights, SG had third harvest biomass values similar to GG, while for the 10-cm cutting-height values were similar to those of BB (Table 3). At the second harvest, SG also had similar yield values to those of GG for the 20-cm cutting-height. During the second year, SG had greater ($P < 0.001$) per harvest and total forage weight values than any other species except GG at the third cut. Generally, GG appeared the second ranked species in forage biomass with both BB and IG showing more or less similar but the least values. The observed species biomass differences demonstrate variations in their abilities to recover from defoliation and the likelihood of altering the subsequent biomass proportions in mixed stands. Usually, plant species differ in their abilities to compensate for defoliation-imposed tissue damages (Dawson et al., 2000) as reflected in respective regrowth rates (van Staalduinen and Anten, 2005). In mixed stands, such differences may lead to subsequent changes in forage biomass (Temu et al., 2014), sward structure, and/species composition (Temu et al., 2015). Owing to differences, in species' ability to restore lost photosynthetic capacities, recovery growths often result in under/overcompensation of preceding tissue damages. Additionally, the notable similarities in BB and IG forage biomass response to intensities of defoliation suggest that harvesting may not drastically alter their proportional contributions to total biomass from shared mixed stands.

3.3.2 Species Average and Relative Growth Rates

Species differences were also observed in the rate at which the NWSGs produced the recorded forage biomass. During the first year, mean AGR values were greater for GG than for any other species except SG at the second and third harvests (Table 3). Towards each harvest, the rate of increase in forage biomass for IG was the least compared to any other species. For all harvests, the AGR values for GG and SG were over 100% greater than those of IG. The RGR for the second cut were greatest for SG, although not significantly different from that for the 10- or 15-cm cut IG. All species generally showed comparable RGR for the third harvest. The second ranked RGR value was for GG and BB that were significantly similar to each other. However, there was no species difference in RGR towards the third harvest. In the second year experiment, AGR values (Table 4) also showed notable differences in species rankings. For every cutting-height, SG had greater AGR values than any other species ($P < 0.001$) towards the first and second harvests, but similar to GG towards the third. There was also no significant AGR difference between BB and IG towards the second or third harvest. The second year species RGR values were greater for GG and the least for BB with no significant difference between IG and SG. These RGR values are comparable to previously reported research results of other NWSGs (Coyne and Bradford, 1995). Over all, SG and GG were the first and second most productive of the four NWSGs, respectively.

3.3.2 Species Belowground Biomass

On the second year data, crown weights were greater ($P < 0.001$) in SG than any other species except for the 10-cm cut GG (Table 4). For each cutting-height, SG also had greater root biomass (up to nearly 50 g) than any other species whose values ranged from as low as 2.6 g in IG to nearly 28.4 g in BB. Except for the 10-cm cut GG, the least crown and root weights were in IG followed by BB and GG, in ascending order. There were significant species differences in their RTB ratios with values in the order of BB > SG > IG > GG. Although comparable diversities in species response to defoliation attributable to differences in compensatory mechanisms have been reported (Meyer, 1998; Smith, 1998; Gutman et al., 2001), the magnitudes of the RTB ratio values, in the current study, suggest that root systems of the more severely impacted species had better efficiencies of obtaining soil-based resources for growth. Plants with better resource uptake and/utilization efficiencies are more likely to survive severe defoliation events, even when their forage productivity declines, which may later on be reversed by appropriate management.

4. Conclusions

There being no effect of root-trimming on all parameters determined, data indicate that, trimming outgrown and/entwined roots to facilitate seedling placement in mechanized planting of NWSGs may not negatively impact their growth or biomass production during establishment, under similar soil moisture and nutrient supply. That with comparable growing conditions, mowing transplanted NWSGs at 20-cm, during establishment, may not negatively impact their growth performance provided they are allowed a ≥ 3-week recovery period. Because the belowground and forage biomass response to treatments were in similar trends, data indicate that severe defoliation during establishment may impact stand persistence, negatively. The demonstrated greater species susceptibilities of BB and IG to tissue damages associated with intensive defoliation suggest that their proportions in frequently harvested mixed stands with GG and/or SG may be drastically reduced.

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