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Research Article

Growth analysis of sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.] in different plant strata

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Abstract

This study evaluated the growth patterns of sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.] across its basal (BS), middle (MS), and apical (AS) strata. The experiment began from April to August 2022 at the Renewable Natural Resources (RNR) greenhouse of the Antonio Narro Autonomous Agrarian University (UAAAN), Saltillo, Coahuila, Mexico. Leaf area index (LAI), specific leaf area (SLA), leaf area duration (LAD), biomass duration (BDM), absolute growth rate (AGR), relative growth rate (RGR), net assimilation rate (NAR), and crop growth rate (CGR), were measured at 14-day intervals over 120 days after sowing (DAS). Means were compared using ANOVA and Tukey's HSD post-hoc test ($p < 0.05$). At 92 DAS, the basal stratum exhibited a maximum LAI of 2.83. The SLA was higher in apical stratum at 120 DAS, reaching 679.1 cm^2 g^{-1}. The highest LAD was recorded in middle stratum at 92 DAS, with a value of 7302.2 cm^2 day^{-1}. The highest BMD was recorded in stratum BS at 120 DAS, with a value of 523 g day^{-1}. The AGR was higher in stratum BS ($p \leq 0.005$), with maximum values recorded at 92 DAS, reaching 0.694 g day^{-1}. The RGR showed the highest growth in basal stratum ($p \leq 0.005$), with a maximum growth recorded at 50 DAS of 0.192 g g^{-1} day^{-1}. Regarding NAR, the highest value was observed in basal stratum at 50 DAS, with 0.0048 g cm^2 day^{-1}. The highest values were also present in stratum BS at 92 DDS, with a value of 0.00364 g cm^2 day^{-1}. The basal stratum showed the greatest increase in all the variables measured, highlighting in RGR, AGR and NAR, indicating its greater productive potential and better-quality forage, useful to optimize management and productivity in pastures with sideoats grama.

Keywords: dry matter yield; growth rates; leaf area; leaf area index; net assimilation rate

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Introduction

Sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.] is a native species that grows on plains and rocky hills and has an excellent forage value for extensive grazing (Hobbs *et al*., 2024). Furthermore, it offers ample forage, adapts to various climates, and is drought resistant. This grass is considered the second most important species in agronomic importance within the *Bouteloua* genus (Morales-Nieto *et al*., 2008). Plants of this species can reach heights of 75 cm or more and have digestibility values that vary between 50 and 70% (Corrales-Lerma *et al*., 2016). Forage production of this plant depends significantly on its phenological stage, maintaining its forage value longer than other grasses (Bell and Smith, 2021).

Most grasslands in Mexico's arid and semi-arid zones are degraded, primarily because of overgrazing (Guerra *et al*., 2006; Jurado-Guerra *et al*., 2021). Also, due to its ability to adapt to a wide range of conditions and its good forage value, *Bouteloua curtipendula* is one of the most widely used species for reseeding grasslands in northern Mexico (Álvarez-Holguín *et al*., 2021).

However, there is little information to help determine the appropriate variety for the different ecoregions of the country. Also, information on the forage value of different plant strata is limited. The strata are distinguishable layers within the vegetation of a structural unit, arranged approximately parallel to the ground and superimposed, thus contributing to a three-dimensional view. Each stratum is defined by distinct resource availability and environmental conditions, which in turn lead to variations in the accumulation of dry matter and its individual components. For instance, the lower strata receive less sunlight but maintain a more constant temperature and higher relative humidity compared to the upper strata (Soto-Rojas *et al*., 2023).

Animals also exhibit a preference for strata, driven by characteristics such as height and morphology, particularly leaf availability, selecting the most desirable plant parts (Shelford, 1912). Therefore, growth analysis is necessary in each stratum of the plant. By using growth analysis, we can find physiological differences between varieties or genotypes of the same species. In recent years, this technique has gained importance in characterizing and selecting genotypes according to their forage potential and requirements (Akram, 2011). In addition, this analysis provides information on the establishment capacity of a plant since high values in growth rates indicate a greater development of both the aboveground biomass and the root system. This allows the plant to capture more resources and facilitate its establishment in the field (Sanaullah *et al*., 2011). Therefore, the objective was to characterize different strata of *Bouteloua curtipendula* on different days after sowing using growth indices.

Materials and Methods

Description of the study area

The experiment started on April 25, 2022, and ended on August 22, 2022, at the Renewable Natural Resources (RNR) greenhouse of the Antonio Narro Autonomous Agrarian University (UAAAN), Saltillo Unit, Coahuila, Mexico (25°35′35″ N, 101°03′60″W), at an altitude of 1,783 m. Using the NdeM-303 variety of *B. curtipendula*.

The maximum, minimum, and average temperatures and relative humidity were estimated using a WS08 model digital hygrometer inside the greenhouse (Figure 1).

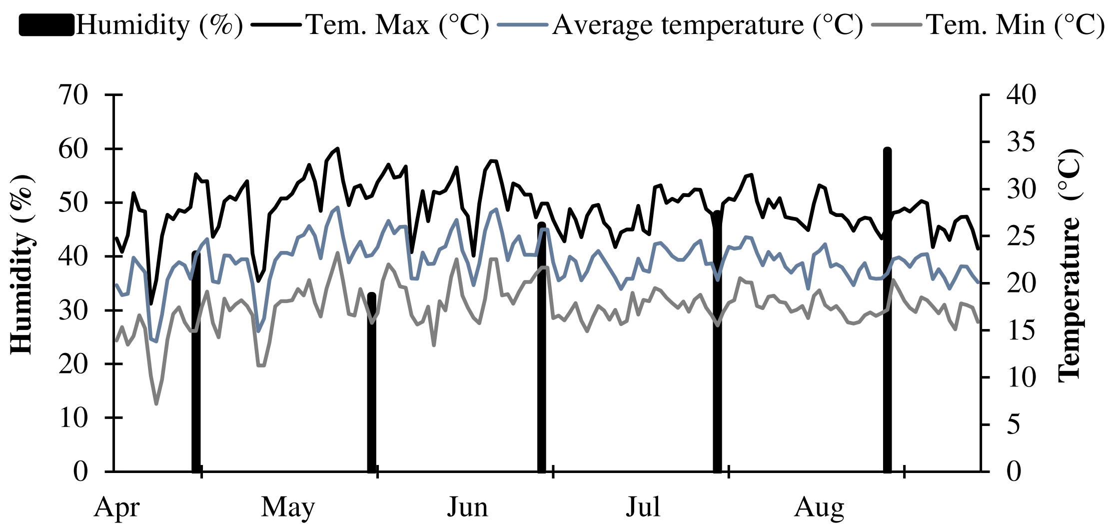

Figure 1. Temperature and humidity data collected at the UAAAN-Saltillo Unit's RNR greenhouse between April 25 and August 23, 2022

Experimental design

The *Bouteloua curtipendula* variety NdeM-303 was used, using plastic pots with a capacity of eight kg. The potting mix, with a clay-loam texture, consisted of 50% mountain soil, 25% peat moss, and 25% vermiculite; it had 26% sand, 38% silt, 36% clay, 2.34% organic carbon, 4.03% organic matter, and 5.93% total nitrogen. The pH was 8.65 ± 0.02, the electrical conductivity, measured in a 2:1 ratio, was 760 ± 32 µS/cm. The apparent density was determined to be 1.15 g/cm^3, with a pore space of 59.8%. Sterilization of the substrate was achieved by moistening and covering it with nylon for four days. Then, 50 visually healthy seeds were sown per pot. Fifteen days later, three of the most vigorous plants were selected for thinning. To improve air flow and water drainage, the pots were placed on wooden pallets. Irrigation varied between 0.5 and 1 liter of water, at field capacity. A completely randomized block experimental design was used, with five repetitions. The treatments were eight destructive cuts at different ages of the plant, with five repetitions. Samples were collected every 15 days from 22 DAS (the point of optimal morphological differentiation) to 120 DAS.

Variables evaluated

Dry matter yield

Using destructive sampling, the entire plant was removed 23 days after planting and placed in labeled paper bags. Then, they were separated according to their length, equally into three strata: Basal Stratum (BS), Middle Stratum (MS) and Apical Stratum (AS). The samples were placed in labeled paper bags and dried in a forced air oven at 55 °C for 72 hours until constant weight, to estimate the dry matter yield.

Leaf area

To estimate the leaf area, fresh leaf samples were separated from the stem and placed on a previously identified white sheet and a centimeter scale. A 30 cm ruler was used on the labeled leaf. Photos of the leaves were used with the scale and analyzed in iMAGEJ software to determine leaf area (*https://imagej.net/ij/download.html*).

<u>Growth rates</u>

Table 1 presents growth indices calculated via the classical and average value methods of Watson (1952) and Zeide (1993).

Table 1. Growth indices used in plant and crop physiology, adapted from Gardner *et al*. (2017)

Growth index	Abbreviation	Symbol	Formula for determining average values for a period (T1 - T2)	Units
Leaf area index	LAI	L	$\text{LAI} = \frac{LA}{SA}$	Dimensional according to units
Specific leaf area	SLA	AE	$\text{SLA} = \frac{\frac{LA2}{W2}+\frac{LA1}{W1}}{2}$	$cm^2\ g^{-1}$
Leaf area duration	LAD	D	$\text{LAD} = \frac{(LA2 + LA1) * (T2 + T1)}{2}$	$cm^2\ day^{-1}$
Biomass duration	BMD	Z	$\text{BMD} = \frac{(W2 + W1)(T2 + T1)}{2}$	$g\ day^{-1}$
Absolute growth rate	AGR	C	$\text{AGR} = \frac{W2-W1}{T2-T1}$	$g\ day^{-1}$
Relative growth rate	RGR	R	$\text{RGR} = \frac{(Ln\ W2-LnW1}{(T2-T1)}$	$g\ g^{-1}\ day^{-1}$
Net assimilation rate	NAR	E	$\text{NAR} = \frac{(W2-W1)}{(T2-T1)} * \frac{(LnLA2-LnLA1)}{(LA2-LA1)}$	$g\ cm^2\ day^{-1}$
Crop growth rate	CGR	CC	$\text{CGR} = \frac{1}{SA} * \frac{(W2-W1)}{(T2-T1)}$	$g\ cm^2\ day^{-1}$

LA = Leaf area; SA = soil area, T = time, W = dry weight.

Statistical analysis

To assess the effects of days after sowing on the variables, an ANOVA was conducted using JMP 14 Pro's PROC GLM. To compare means between treatments, Tukey's post-hoc test was applied, establishing a significance level of $\alpha = 0.05$.

Results

Leaf area (LA)

Figure 2 shows the leaf area (LA) of *Bouteloua curtipendula* at different plant strata, where statistical differences were observed ($p < 0.05$). In the basal stratum, the highest and lowest values were observed at 92 and 22 DAS with 541.6 and 1.09 cm^2 $plant^{-1}$, respectively ($p > 0.05$). In the middle stratum, the highest value was recorded at 92 DAS with 526 cm^2 $plant^{-1}$ and the lowest at 22 DAS with 2.3 cm^2, while in the apical stratum (AS), at ages of 92 and 78 DAS, the highest amounts of leaf area were 175 and 150 cm^2 $plant^{-1}$ and the lowest value at 22 DAS with 2.1 cm^2 ($p > 0.05$).

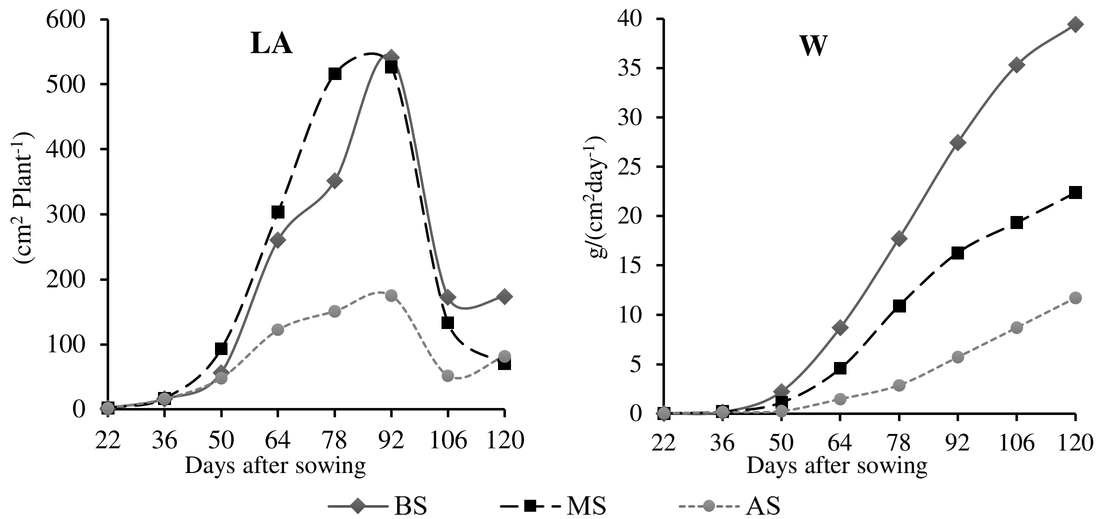

Figure 2. Growth analysis of different strata of *Bouteloua curtipendula* throughout days after sowing.
BS = Basal stratum, MS = Middle stratum, and AS = Apical stratum. LA = Leaf area, W = Dry mass

Dry mass (W)

Figure 2 shows the dry mass (W) production in three plant strata, where all strata showed exponential growth. The Basal Stratum (BS), registered the highest value with 39.4, followed by the Middle Stratum (MS) stratum with 22.4 and the Apical Stratum (AS) with 11.7 g DM stratum^{-1} plant^{-1}, where the percentage differences were 54, 30 and 16% in the BS, MS, and AS strata, respectively.

For the analysis of dry mass and leaf area, regression equations were determined using third-degree polynomial models (Table 2). The selected models presented a correlation coefficient (r^2) greater than 0.70, indicating an adequate predictive capacity.
The general expression of these models is $y = cx^2 \pm bx \pm a$, where y represents the dependent variable (dry mass or leaf area), and x is the independent variable (DAS). The corresponding growth indices were calculated according to the formulas detailed in Table 1, allowing an accurate evaluation of plant growth parameters.

Table 2. Regression equations for leaf area and dry mass values of the three evaluated strata of *Bouteloua curtipendula*

Cultivars resistant	Variable	Equation	R^2
BS	Foliar area	$y = -0.003x^3 + 0.5331x^2 - 22.008x + 250.66$	0.77
	Dry mass	$y = -1E-04x^3 + 0.0231x^2 - 1.2046x + 16.888$	0.99
MS	Foliar area	$y = -0.0035x^3 + 0.5801x^2 - 21.267x + 204.27$	0.80
	Dry mass	$y = -6E-05x^3 + 0.0141x^2 - 0.7326x + 10.289$	0.99
AS	Foliar area	$y = -0.0006x^3 + 0.0753x^2 - 0.3871x - 30.637$	0.73
	Dry mass	$y = -3E-06x^3 + 0.0023x^2 - 0.1443x + 2.275$	0.99

BS: Basal Stratum; MS: Middle Stratum; AS: Apical Stratum.

Leaf area index (LAI)

Figure 3 shows the LAI with the highest values in the basal stratum of the plant (BS), presenting significant differences ($p \leq 0.005$) (Table 3). At 92 DAS, the highest values were observed in all strata (BS=2.83, MS = 2.76, AS = 0.91). Nevertheless, BS and MS were higher than AS, which indicates that they have a greater photosynthetic capacity and is directly related to the production of dry matter. Therefore, when the LAI is high, a greater accumulation of dry matter is expected.

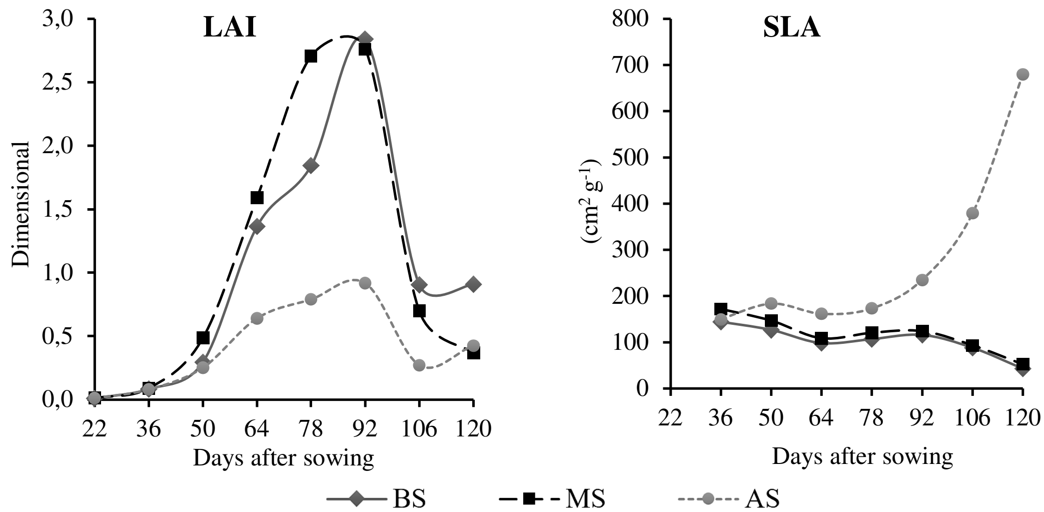

Figure 3. Leaf growth indices of *Bouteloua curtipe dula* at different plant strata
BS = Basal stratum, MS = Middle stratum, and AS = Apical stratum, and days after sowing (DAS), considering the following growth rates: (LAI = Leaf area index, SLA = Specific leaf area)

Table 3. Comparison of growth rates of sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.] in different strata during April and August 2022, at different DAS

Stratum	DAS	LAI		SLA $cm^2\ g^{-1}$		LAD $cm^2\ day^{-1}$		BMD $g\ day^{-1}$		AGR $g\ day^{-1}$		RGR $g\ g^{-1}\ day^{-1}$		NAR $g\ cm^2\ day^{-1}$		CGR $g\ cm^2\ day^{-1}$	
BS	22	0.01	e														
	36	0.08	e	144.2	a	125.2	d	1.1	f	0.009	d	0.147	b	0.0014	c	0.00005	d
	50	0.29	de	126.5	ab	506.0	d	16.5	ef	0.147	cd	0.192	a	0.0048	a	0.00077	cd
	64	1.36	bc	98.2	bc	2217.9	c	76.3	e	0.463	abc	0.100	c	0.0035	ab	0.00243	abc
	78	1.84	b	107.0	abc	4284.3	b	185.0	d	0.646	ab	0.051	d	0.0022	bc	0.00338	ab
	92	2.83	a	115.9	abc	6251.9	a	316.4	c	0.694	a	0.032	de	0.0017	bc	0.00364	a
	106	0.90	cd	88.2	c	4998.5	ab	439.3	b	0.560	ab	0.018	de	0.0019	bc	0.00293	ab
	120	0.90	cd	43.2	d	2421.6	c	523.0	a	0.295	bcd	0.008	e	0.0016	bc	0.00155	bcd
	Pr > F	≤.0001*		≤.0001*		≤.0001*		≤.0001*		≤.0001*		≤.0001*		≤.0001*		≤.0001*	
	SE	0.15		5.8		381.0		33.4		0.050		0.012		0.0003		0.00026	
MS	22	0.01	e														
	36	0.09	de	171.6	a	136.4	f	1.5	f	0.012	b	0.146	a	0.0016	ab	0.00006	c
	50	0.48	cd	146.8	ab	769.8	ef	9.1	f	0.066	b	0.121	ab	0.0015	ab	0.00035	bc
	64	1.59	b	108.6	b	2774.8	d	39.8	e	0.246	ab	0.101	bc	0.0014	ab	0.00129	ab
	78	2.70	a	120.4	ab	5739.0	b	108.2	d	0.452	a	0.065	cd	0.0012	b	0.00237	a
	92	2.76	a	124.2	ab	7302.2	a	190.3	c	0.386	a	0.029	de	0.0007	b	0.00202	a
	106	0.69	c	93.4	bc	4618.6	c	249.3	b	0.217	ab	0.013	e	0.0007	b	0.00114	abc
	120	0.36	cde	52.4	c	1421.2	e	291.9	a	0.217	ab	0.010	e	0.0022	a	0.00114	abc
	Pr > F	≤.0001*		≤.0001*		≤.0001*		≤.0001*		≤.0001*		≤.0001*		0.0007*		≤.0001*	
	SE	0.17		434.6		434.6		18.8		0.031		0.009		0.00014		0.00017	
AS	22	0.01	d														
	36	0.08	d	149.4	b	122.2	f	1.1	e	0.009	b	0.147	a	0.0014	ab	0.00005	a
	50	0.25	cd	183.7	b	443.9	ef	2.7	e	0.006	b	0.032	b	0.0002	b	0.00003	a
	64	0.64	ab	161.5	b	1192.7	cd	11.9	de	0.088	ab	0.129	a	0.0012	ab	0.00046	a
	78	0.79	a	173.2	b	1911.5	ab	30.3	d	0.100	ab	0.048	b	0.0008	b	0.00052	a
	92	0.91	a	234.6	b	2280.2	a	60.1	c	0.204	a	0.051	b	0.0012	ab	0.00107	a
	106	0.27	cd	379.1	b	1587.8	bc	101.0	b	0.213	a	0.030	b	0.0025	ab	0.00112	a
	120	0.42	bc	679.1	a	931.1	de	142.9	a	0.214	a	0.023	b	0.0058	a	0.00112	a
	Pr > F	≤.0001*		≤.0001*		≤.0001*		≤.0001*		0.0025*		≤.0001*		0.0156*		0.0343	
	SE	0.0541		37.6		130.9		8.7		0.020		0.009		0.0005		0.00011	

Averages followed by the same letter in the same column do not differ ($p > 0.05$). Sig. = Significance. SE = Standard error. BS= Basal stratum. MS= Middle stratum. AS = Apical stratum. * = Significative. AGR = Absolute growth rate, RGR = Relative growth rate, NAR = Net assimilation rate, CGR = Crop growth rate, LAI = Leaf area index, SLA = Specific leaf area, LAD = Leaf area duration, BMD = Biomass duration

Specific leaf area (SLA)

Unlike LAI, the highest SLA was recorded in the apical stratum (Figure 3). A significant difference ($p \leq 0.005$) was observed with maximum values at 106 and 120 DAS, reaching 379.1 and 679.1 $cm^2\ g^{-1}$, and minimum values at 36 DAS, with 149.4 $cm^2\ g^{-1}$. For the middle stratum (MS), there was also a significant difference between DAS ($p \leq 0.005$), where the maximum SLA was recorded at 36 DAS with 171.6 $cm^2\ g^{-1}$, and a drastic drop at 120 DAS with 52.4 $cm^2\ g^{-1}$ (Table 3). On the other hand, the basal stratum (BS) showed significant differences ($p \leq 0.005$), with the highest SLA at 36 DAS with 144.2 $cm^2\ g^{-1}$, and the lowest at 120 DAS with a value of 43.2 $cm^2\ g^{-1}$.

Leaf area duration (LAD)

Figure 4 shows the LAD, where a significant difference ($p \leq 0.005$) is observed in relation to the DAS (Table 3). The highest LAD was recorded at 92 DAS in all strata, with the middle stratum presenting a maximum value of 7302.2 $cm^2\ day^{-1}$, followed by the basal stratum with 6251.9 $cm^2\ day^{-1}$, and the lowest value was observed in the apical stratum with 2280.2 $cm^2\ day^{-1}$.

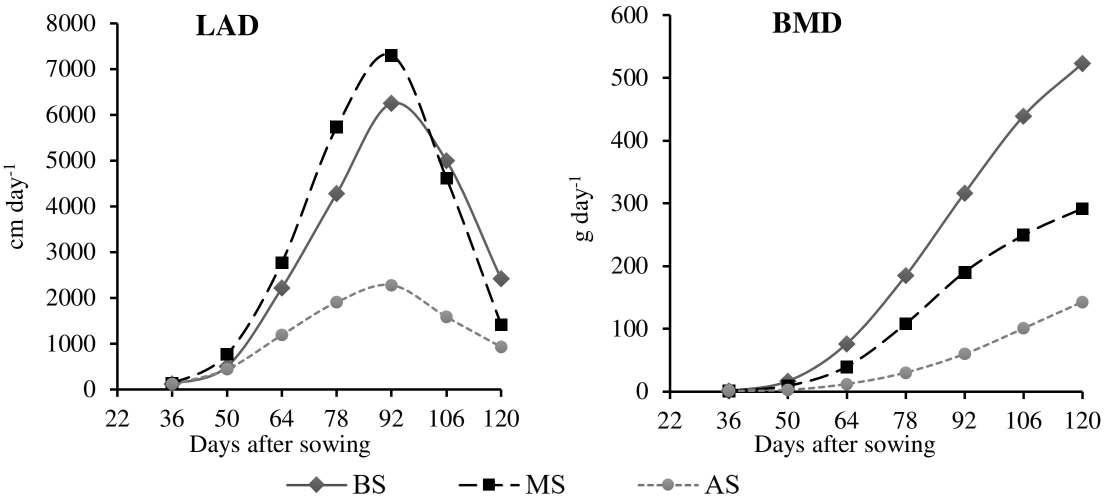

Figure 4. Analysis of biomass duration of *Bouteloua curtipendula* at different strata
BS = Basal stratum, MS = Middle stratum, AS = Apical stratum, considering the following growth rates: LAD = Leaf area duration, BMD = Biomass duration

Biomass duration (BMD)

Statistically significant differences ($p \leq 0.005$, Table 3) in BMD duration across three strata were observed in relation to DAS, as shown in Figure 4. In the basal stratum, an exponential increase was recorded, reaching a maximum duration at 120 DAS with a value of 523 $g\ day^{-1}$. Similarly, the MS and AS strata also showed exponential growth, reaching their maximum values at 120 DAS, with 291.9 and 142.9 $g\ day^{-1}$, respectively.

Growth rate

Absolute growth rate (AGR)

The AGR is a critical indicator that represents the first slope in the dry mass accumulation curve of plants, allowing to estimate the amount of water and photoassimilates required by the aerial part of the plant for its development (Di Benedetto and Tognetti, 2016; Cai *et al.*, 2023). Figure 5 shows the significant differences observed in the different strata ($p \leq 0.005$). In the basal stratum, the maximum values were recorded at 78, 92 and 106 DAS, with values of 0.646, 0.694 and 0.560 $g\ day^{-1}$, respectively, while the lowest value was observed at 22 DAS with 0.009 $g\ day^{-1}$. In the middle stratum (MS), a significant difference was also observed between DAS ($p \leq 0.005$), where the highest AGR was reached at 92 and 78 DAS with 0.386 and 0.452 g day^{-1}, respectively, and the lowest was 0.012 g day^{-1} at 36 DAS. Likewise, in the apical stratum, significant differences were also observed ($p \leq 0.005$), with the highest production observed at 92, 106 and 120 DAS with 0.204, 0.213 and 0.214 g day^{-1}, respectively while the lowest production values occurred at 22 and 36 DAS with 0.009 and 0.006 g day^{-1}, respectively.

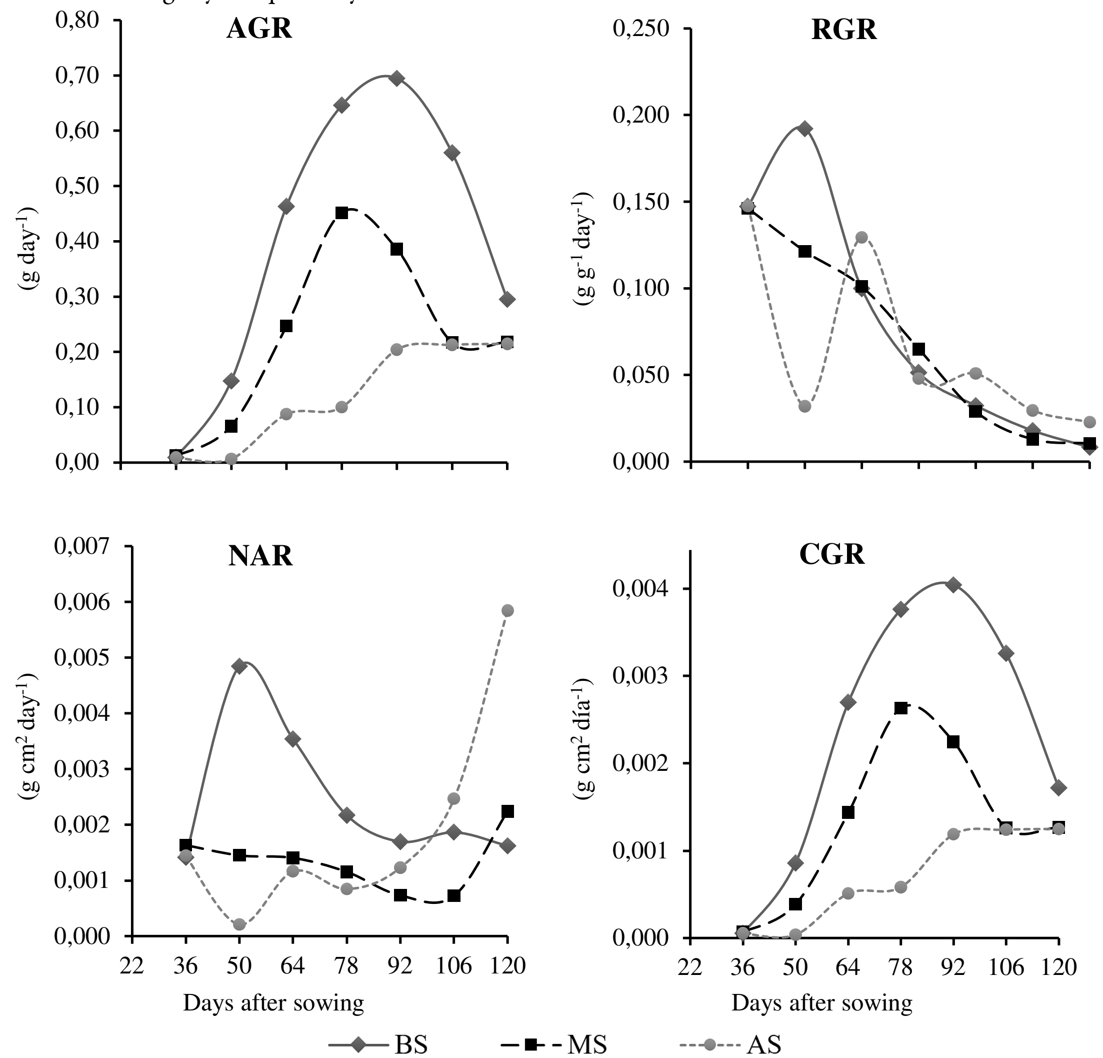

Figure 5. Growth rates of *Bouteloua curtipendula* at different plant strata
BS = Basal stratum, MS = Middle stratum, and AS = Apical stratum. AGR = Absolute growth rate, RGR = Relative growth rate, NAR = Net assimilation rate, CGR = Crop growth rate

<u>Relative growth rate (RGR)</u>

Significant differences were found in all the plant strata (Figure 5; Table 3; $p < 0.05$). It was observed that the highest RGR occurred in the basal stratum, with maximum growth at 50 DAS with 0.192 g g^{-1} day^{-1}, followed by 36 DAS with 0.147 g g^{-1} day^{-1}, while the lowest growth at 120 DAS with 0.008 g g^{-1} day^{-1}. In the middle stratum, the maximum growth was recorded at 36 DAS with a value of 0.146 g g^{-1} day^{-1}, followed by 50 DAS with 0.121 g g^{-1} day^{-1}. The lowest values were found at 106 and 120 DAS, with 0.013 and 0.010 g g^{-1} day^{-1}. In the apical stratum, the highest values were found at 36 and 64 DAS, with values of 0.147 and 0.129 g g^{-1} day^{-1}, respectively. The lowest values ranged between 0.030 and 0.023 g g^{-1} day^{-1}, at 106 and 120 DAS.

Net assimilation rate (NAR)

The NAR showed statistical differences throughout DAS in the basal and middle stratum ($p < 0.05$), but not in the apical stratum (Figure 5; Table 3; $p > 0.05$). In the basal stratum, the highest NAR was found at 50 DAS with 0.0048 g cm^2 day^{-1}, followed by 64 DAS with 0.0035 g cm^2 day^{-1}. The lowest result was obtained at 36 DAS with 0.0014 g cm^2 day^{-1}. In the middle stratum, the highest NAR values were observed at 120 DAS, with 0.0022 g cm^2 day^{-1}. For the apical stratum, an exponential growth in the NAR was observed, starting at 92, 106 and 120 DAS with values of 0.0012, 0.0025 and 0.0058 g cm^2 day^{-1}.

Crop growth rate (CGR)

In CGR only in the basal and middle stratum, significant differences ($p \leq 0.005$) were observed (Figure 5; Table 3). In the BS, the maximum values were observed at 78 and 92 DAS with values of 0.00338 and 0.00364 g cm^2 day^{-1}, respectively. The lowest values were observed at 36 DAS with 0.00005 g cm^2 day^{-1}. In the MS, the highest values were recorded at 78 and 82 DAS with values of 0.00237 and 0.00202 g cm^2 day^{-1} respectively, and the lowest values were observed at 36 and 50 DAS with 0.0016 and 0.0015 g cm^2 day^{-1}. On the other hand, the apical stratum did not present significant differences ($p \geq 0.005$), but a higher value was observed at the end of the study at 120 DAS with a value of 0.000112 g cm^2 day^{-1}.

Discussion

Leaf area peaked at different ages depending on the stratum, yet the minimum was uniformly observed at 22 DAS, attributable to the onset of plant growth. Di Benedetto and Tognetti (2016) found that increased leaf area directly impacts photosynthesis (photoassimilate production) and respiration. In this study, the middle stratum, MS, showed the greatest growth in LA, compared to BS and AS, evidencing a more intense leaf development with exponential growth until the flowering phase, since after this, the FA growth decreases considerably. Sáez-Cigarruista *et al.* (2024) reported similar trends when studying the behaviour of sunflowers, and Zhang *et al.* (2019) point out that another factor that contributes to the decrease in FA at the end of the crop cycle is the senescence process of the basal leaves, either by completing their phenological cycle in annual plants or by self-shading in perennial plants.

These findings suggest that the accelerated growth phase begins after 36 days after sowing (DAS) in the BS and MS strata, but not in the AS stratum. Throughout its development, the AS stratum maintains a smaller leaf area, and at more advanced stages it produces an inflorescence with a lower weight than that observed in the other strata (Soto-Rojas *et al.*, 2023).

Leaf area index (LAI) is a measure that helps determine a plant's photosynthetic potential on a particular soil surface (Borrego *et al.*, 2000). According to Di Benedetto and Tognetti (2016), leaf area directly impacts photosynthetic (photoassimilate production) and respiratory processes. This study shows that increased basal leaf area correlates with more intense leaf development, exhibiting exponential growth until flowering. After this phase, the growth of the LAI decreases considerably (Figure 3). Guzmán *et al.* (2021) found that larger *Bouteloua curtipendula* caryopses and embryos correlated with a higher leaf area index, peaking at 80 DAS, suggesting improved solar radiation capture and establish themselves efficiently. On the other hand, Zhang *et al.* (2019) indicated that senescence of basal leaves is another factor that contributes to the reduction of leaf area towards the end of the crop cycle.

Specific leaf area (SLA) is defined as the ratio between leaf area and leaf weight and is an index of leaf thickness and density (Souza *et al.*, 2019). The higher leaf weight per cm of FA in the upper strata of the plant is due to the plant's physiology. This is because the older middle and basal strata have more senescent material that decreases their weight, unlike the younger leaves in the upper strata (Soto-Rojas *et al.*, 2023). According to Guzmán *et al*. (2021), the specific leaf area curves in *Bouteloua gracilis* show a gradual increase, attributed to a greater renewal of the leaf blades. This phenomenon has been previously described by Gastal and Lemaire (2015), who observed that the appearance of successive leaves can decrease during plant development, and that the decrease in leaves is systematically associated with an increase in the length of the sheath and the blade. Davies *et al*. (1983) suggests that the length of the sheath tube of older leaves may affect the appearance of younger growing leaves. In contrast, *Bouteloua curtipendula* shows decreasing SLA in BS and MS, attributable to early leaf senescence. In contrast, AS increases SLA from 92 DAS, reflecting younger leaves that are more efficient at capturing light and fixing carbon. This stratified turnover suggests an adaptive strategy to optimize resources, conserving the most productive fraction at the top and discarding the less efficient fraction at the base.

The concept of leaf area duration (LAD), defined as the integral of LAI over time, was suggested by Watson (1947) in his study of LAI dynamics, emphasizing both area and temporal persistence. The results obtained show that the LAD showed a greater increase up to 92 DAS. Aguilar-García *et al*. (2005) observed that leaf area duration in sunflower was extended due to population density, particularly before flowering. They recorded a maximum LAD of 219.8 days under high population density conditions attributable to the increase in the leaf area index. Vega-Muñoz *et al*. (2001) and Aguilar-García *et al*. (2002) reported comparable effects in sunflower cv. Victoria under rainfed conditions, where a higher LAD at high population densities translates into an increase in biomass production, resulting from a greater interception of solar radiation by the plant canopy.

Plant biomass over time, measured by total dry weight, offers an indirect way to gauge how long a plant remains alive and healthy. This index measures not just the dry weight increase, but also how durable it is (Kvet *et al*., 1971). The results are particularly important because high biomass durability is associated with positive population values. Exponential growth was recorded in BS, MS, and AS, reaching its greatest duration at 120 DAS. Biomass duration reflects the capacity to maintain functional structure, optimizing resources and ecological performance; leaf longevity is closely related to structural and functional characteristics of the leaves (Reich *et al*., 1991). The increase in biomass in these strata suggests phenotypic or genetic adaptation, driving population persistence (Fox *et al*., 2019). Maintaining high biomass levels promotes vegetation cover, reduces erosion, and improves nutrient retention and water infiltration (Blanco-Canqui *et al*., 2017). Monitoring total dry weight throughout growth is essential for assessing plant dynamics and designing conservation and sustainable management strategies in agroecosystems and natural environments (Marcelis *et al*., 1992).

Growth rate

The Absolute Growth Rate (AGR) is the first derivate or slope of the dry mass accumulation curve (Di Benedetto and Tognetti, 2016). In the BS, the AGR had a greater accumulation of g day^{-1} during the longitudinal growth phase of the stem, until the end of flowering. The MS reached its highest accumulation rate (g day^{-1}) at 78 DAS, followed by a decline at 106 and 120 DAS. In contrast, the AS showed a sustained increase from 64 DAS, stabilizing between 92 and 120 DAS; however, it maintained the lowest accumulation of g day^{-1} compared to the other strata evaluated. A fundamental parameter for understanding growth dynamics across environments and treatments is AGR, whose variation over time has been confirmed by recent research (Carrillo-Criollo and Yumbla-Orbes, 2022).

According to James and Drenovsky (2007), the Relative Growth Rate (RGR) expresses the capacity of a plant to produce new material from a unit of weight. In all three strata analyzed, the RGR starts at the same level. In the BS, the RGR reaches its maximum at 50 DAS, then progressively decreases to 120 DAS. In contrast, the MS shows a more uniform decrease in RGR throughout the evaluation period. Meanwhile, the AS experiences a pronounced drop in RGR at 50 DAS, followed by a moderate increase and, subsequently, a further decline, culminating in the lowest value at 120 DAS. This is because, mathematically, RGR estimates a plant's capacity for new meristematic tissue generation as it ages, using the natural logarithm of its dry mass over time, and focusing on photoassimilate translocation to developing organs. Therefore, RGR provides a more detailed view of the efficiency with which a plant can convert resources into new vegetative tissue (Polat *et al.*, 2020). In the study of Reich *et al.* (2003) on nitrogen fertilization's impact on 34 grassland species revealed sideoats grama RGRs of 0.136 g g^{-1} day^{-1} (fertilized) and 0.105 g $g^{-1}day^{-1}$ (unfertilized).

The Net Assimilation Rate (NAR) indicates the amount of accumulated biomass as a function of leaf area (Bauchi *et al.*, 2023). The stratum with the highest average NAR, with a value of 0.0024 g cm^2 day^{-1}, corresponded to the basal stratum (BS). This result coincided with the highest average RGR, which reached 0.078 g g^{-1} day^{-1} which explains its outstanding performance in the production of aboveground biomass (Figure 2), since the Net Assimilation Rate is used as an indicator of the efficiency with which the photosynthetic tissue captures and uses solar radiation to produce dry mass through laminar photosynthesis (Rosales *et al.*, 2011). This metric reflects the capacity of plant materials to optimize the use of solar radiation suggesting that those with higher NAR values can generate a greater amount of dry matter (Bauchi *et al.*, 2023). These findings show a similar photosynthetic efficiency compared to the results obtained by Holguín *et al.* (2017), who reported NAR values of 0.00495 g cm^2 day^{-1} in flag grass ecotypes at 70 DAS under greenhouse conditions.

Crop Growth Rate (CGR) is a key indicator of agricultural productivity, applied in various crops. This metric quantifies the increase in dry matter yield in plants or plant populations per unit area and time. The CGR in the basal and middle strata shows an exponential growth towards 78 DAS and then tends to decline at 120 DAS. However, the apical stratum, although with less growth, tends to be like the middle stratum at the end of the study. The apical stratum accumulates less initial biomass due to its limited interception of light and photosynthesis (Zhang *et al.*, 2022). As crop development progresses, its photosynthetic efficiency increases, equating its CGR to the middle stratum in later phases (Honda *et al.*, 2021). According to Aguilar-Carpio *et al.* (2015), in a study on corn crops, observed that the highest CGR was recorded 20 days after sowing, in the hybrid H-562 with a fertilization of 160 kg N ha^{-1}, given that this crop as an annual crop, the growth rate is higher vs perennial grasses such as *Bouteloua curtipendula*. The results showed a quadratic relationship, indicating a production of 0.60 g cm^2 day^{-1}, so Woo *et al.* (2004) suggest that nitrogen significantly improves the efficiency of plants in the production of dry matter yield.

Conclusions

The growth in leaf area, dry mass and leaf area index of *Bouteloua curtipendula* were higher in the basal stratum, followed by the middle and apical stratum. This pattern reflects exponential growth until flowering, which is associated with higher dry matter production. However, a higher specific leaf area was reflected in the apical stratum. The greatest leaf area duration was found in a middle stratum. This data demonstrates the impact of biomass and leaf area distribution on photosynthetic efficiency and growth.

Authors' Contributions

Conceptualization: S.J.-M and P. A.-V; Data curation: S.J.-M; Funding acquisition: P. A.-V; Investigation; P. A.-V, J.I.G.-L and S.J.-M; Methodology: P. A.-V, S.J.-M, and J.I.G.-L; Project administration: P. A.-V; Supervision: P. A.-V and J.I.G.-L; Writing - original draft: S.J.-M and P. A.-V; Review and editing: P. A.-V and S.J.-M.

All authors read and approved the final manuscript.

Ethical approval (for research involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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