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Morphophysiological indicators, phenophase and cutting time in an irrigated forage cactus–sorghum intercropping system under strategies of agricultural resilience and agriculture biosaline

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Abstract

The objective of this study was to evaluate growth and development in an irrigated forage cactus–sorghum intercropping system under different strategies for improving agricultural resilience. The research was carried out from 2018 to 2020 in Serra Talhada, Pernambuco, Brazil, in four experiments in a randomized block design, each with four replications. The first experiment consisted of different configurations for the cactus–sorghum intercropping system (Orelha de Elefante Mexicana [OEM]-single crop [SNG], IPA Sertânia [IPA]-SNG, Miúda [MIU]-SNG, OEM–SF11, OEM–Progenitor 288 [P.288], OEM–467, IPA–SF11, IPA–P.288, IPA–467, MIU–SF11, MIU–P.288 and MIU–467); in the second and third experiments, the cactus–sorghum system was planted under different planting densities (100,000; 50,000; 33,333; 25,000 and 20,000 plants ha^{-1} for forage cactus and 200,000 plants ha^{-1} for sorghum) in east–west and north–south orientations, respectively; and the fourth experiment consisted of different planting densities for the cactus and sorghum (50,000; 40,000; 33,333; and 28,571 plants ha^{-1} and 200,000; 160,000; 133,333; and 114,285 plants ha^{-1}, respectively). The maximum values of the dry matter accumulation rate were observed in the cultivation configurations that

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contained the OEM clone and at the highest densities. The different cultivation configurations affected the duration and number of phenophases. The cutting time increases as the planting density increases (50,000 and 100,000 plants ha^{-1}) and when the OEM clone is used.

KEYWORDS

Nopalea cochenillifera, *Opuntia stricta*, planting density and planting orientation, *Sorghum bicolor*

Résumé

L'objectif de cette étude était d'évaluer la croissance et le développement dans un système irrigué de culture mixte de cactus-sorgho et fourrage dans le cadre de différentes stratégies visant à améliorer la résilience agricole. La recherche a été menée de 2018 à 2020 à Serra Talhada, Pernambuco, Brésil, dans quatre expériences selon un plan en blocs aléatoire, chacune avec quatre réplications. La première expérience a consisté en différentes configurations du système de culture mixte de cactus-sorgho (OEM-SNG, IPA-SNG, MIU-SNG, OEM-SF11, OEM-P.288, OEM-467, IPA-SF11, IPA-P.288, IPA-467, MIU-SF11, MIU-P. 288 et MIU-467); Dans les deuxième et troisième expériences, le système cactus-sorgho sous différentes densités de plantation (100,000; 50,000; 33,333; 25,000 et 20,000 plantes ha^{-1} pour le cactus fourrager et 200,000 plantes ha^{-1} pour le sorgho) dans les orientations est-ouest et nord-sud, respectivement; et la quatrième expérience a consisté en différentes densités de plantation pour le cactus et le sorgho (50.000; 40,000; 33,333; 28,571 plantes ha^{-1} et 200,000; 160,000; 133,333; 114,285 plantes ha^{-1}, respectivement). Les valeurs maximales du taux d'accumulation de matière sèche ont été observées dans les configurations de culture contenant le clone OEM et dans les densités les plus élevées. Les différentes configurations de culture ont influé sur la durée et le nombre de phénophases. Le temps de coupe augmente à mesure que la densité de plantation augmente (50,000 et 100,000 plantes ha-1) et lorsque le clone OEM est utilisé.

MOTS CLÉS

Opuntia stricta, *Nopalea cochenillifera*, *Sorghum bicolor*, densité et orientation de plantation

1 | INTRODUCTION

The increase in the demand for forage is a reflection of both increased consumption of animal products and population growth (Alves et al., 2022; Santos, de Oliveira, et al., 2024). Consequently, there have been notable enhancements in resource utilization, particularly in optimizing already arable areas to mitigate the risk of environmental degradation (Zhang et al., 2019). This effect is particularly pronounced in semi-arid climates, where crops are more susceptible to adverse environmental conditions (Jardim et al., 2020; Jardim et al., 2023a).

The use of forage species adapted to the climate conditions of a region is essential for successful farming. Among other crops in a semi-arid environment, forage cactus (*Opuntia* spp. and *Nopalea* spp.) plays an important role in the agricultural sector because it adapts to adverse conditions by modifying its physiological, anatomical and structural characteristics, tolerating high temperatures and water stress and exhibiting high biomass production (Alves et al., 2019; Araújo Júnior et al., 2021a; Queiroz et al., 2016; Pinheiro et al., 2014; Silva et al., 2015). In addition to the forage cactus, another crop that deserves mention is sorghum (*Sorghum* spp.) due to its adaptive characteristics, high resource use efficiency and high productivity, making a combination of these plants important for maximizing animal performance (Jardim et al., 2021).

Although these crops are adapted to the soil and climate conditions, they can present better results when subjected to practices for improving agricultural resilience (Carvalho et al., 2017; Santos, Jardim, et al., 2024). Among such practices are the use of an intercropping system, efficient irrigation, population density and suitable crop orientation.

Among intercropping systems in semi-arid environments, the adoption of a cactus–sorghum system is an efficient strategy for using available resources as it promotes high forage production and increased crop profitability and maximizes results when associated with the application of irrigation depths to complement rainfall (Diniz et al., 2017; Salvador et al., 2024).

The search for the best planting density and crop orientation is of fundamental importance for exploiting the resources found on the property, the first associated with the best use of the area (Alves et al., 2022; Hou et al., 2020) and the second with light interception by the crops (Oliveira et al., 2012). Studies have shown that with an increase in planting density (up to 80,000 plants ha^{-1}) and the choice of forage cactus genotype, system productivity increases, with changes in the growth characteristics of the crop (Cavalcante et al., 2014; Silva et al., 2014a). In a study with forage cactus under different production arrangements, Peixoto et al. (2018) reported that changing the planting orientation (north–south or east–west) promoted a change in productivity, an increase in light capture and, consequently, an increase in the photosynthetic process.

For the cactus–sorghum intercropping system, there is still a gap regarding crop growth and development due to changes in the production system, mainly in relation to the characteristics of sorghum in these productive arrangements. Therefore, it is important to understand the morphological attributes that contribute to crop productivity, including phenological delimitation, since one result of applying agronomic practices may be a delay or acceleration in the start and duration of each phase, affecting dry matter accumulation in the plant and, as a result, the ideal harvest time (Amorim et al., 2017; Jardim et al., 2023b).

In addition, a better understanding of the performance of forage cactus and sorghum plants subjected to different resilience practices can be obtained by applying morphophysiological indices, such as the absolute growth rate (AGR), relative growth rate (RGR), net assimilation rate (NAR), specific cladode/leaf area (SCA/SLA), leaf area ratio (LAR) and leaf mass ratio (LMR) (Queiroz et al., 2015; Silva et al., 2009).

Given the above, the hypothesis is that the selection of the cultivation system promotes changes in morphophysiological characteristics, with a tendency towards greater accumulation of dry matter and anticipation of harvest in the cactus–sorghum production system containing the Orelha de Elefante Mexicana (OEM) forage cactus clone associated with higher-density planting. In this way, the aim of this study was to determine the morphophysiological indicators, phenological phases and cutting time of irrigated forage cactus intercropped with sorghum under different production systems to improve agricultural resilience in a semi-arid environment.

2 | MATERIALS AND METHODS

2.1 | Site of the experiment

The research was carried out from August 2018 to July 2020 at the International Reference Centre for Agrometeorological Studies of the Cactus and other Forage Plants, REF Centre, located at the Serra Talhada Academic Unit of the Federal Rural University of Pernambuco (UFRPE/UAST), in the district of Serra Talhada, Pernambuco, Brazil (7°56′20″ S, 38°17′31″ W and an altitude of 431 m).

According to the Köppen classification, the climate in the region is type BSwh', with rainfall concentrated during the summer and a dry period during the winter (Alvares et al., 2013), a mean air temperature of 26.5°C, a relative humidity of 63%, a mean annual rainfall of 642 mm and an annual atmospheric demand greater than 1800 mm (Pereira et al., 2015; Silva et al., 2015).

The soil in the experimental area is classified as a Cambisol according to the World Reference Base for Soil Resources and has a loamy sand texture. In addition, it has a flat relief and physicochemical characteristics at depths of 0–0.20 m as described below: bulk density = 1.45 g dm^{-3}; total soil porosity = 42.27%; sand = 828.60 g kg^{-1}; silt = 148.225 g kg^{-1}; clay = 23.1 g kg^{-1}; pH (water) = 5.95; electrical conductivity of the saturation extract (EC_{se}) = 0.32 dS m^{-1}; P = 168.96 mg dm^{-3}; Ca^{2+} = 3.45 $cmol_c$ dm^{-3}; K^+ = 13.8 $cmol_c$ dm^{-3}; Na^+ = 1.09 $cmol_c$ dm^{-3}; sum of bases = 20.25 $cmol_c$ dm^{-3}; base saturation = 97.15%; $C_{organic}$ = 4.6 g kg^{-1}; organic matter = 7.93 g kg^{-1}; and cation exchange capacity = 20.85 $cmol_c$ dm^{-3}.

2.2 | Experimental design and crop management

The research was divided into four experimental areas, with differences in the treatments, forage cactus clones

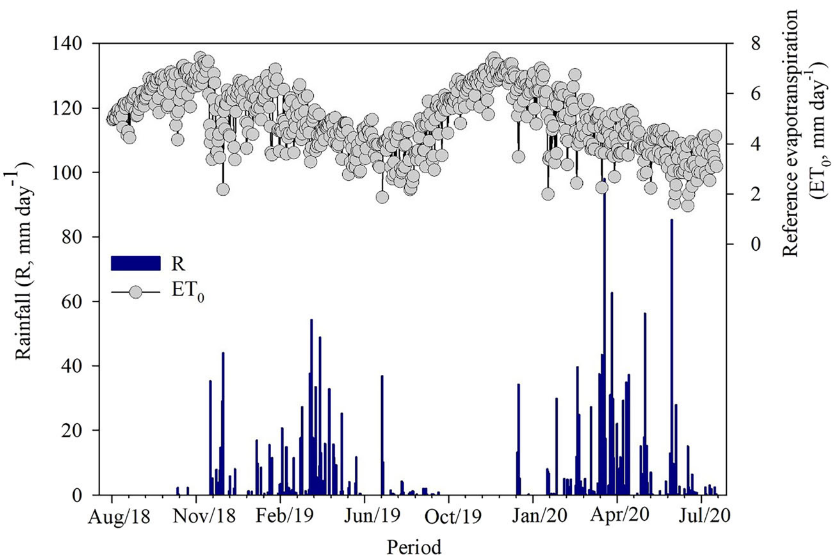

FIGURE 1 Reference evapotranspiration (ET_0) and rainfall (R) from August 2018 to July 2020 in Serra Talhada, Pernambuco, Brazil.

and sorghum cultivars used. The design employed in each experiment was a randomized block design (RBD) with four replications. Prior to planting, the soil was ploughed, harrowed and furrowed. The forage cactus cladodes were then planted in double rows, with 50% of the total length of the cladode inserted into the soil. For this purpose, healthy cladodes from a 3-year-old cultivated forage cactus were chosen from the middle third. The selected cladodes were carefully cut at their insertion points, healed and then planted. The sorghum cultivars were sown in furrows parallel to the rows of forage cactus at a depth of 0.05 m and 0.25 m from the basal cladode of the forage cactus. Weeding was carried out whenever necessary to favour optimal crop growth. In turn, no herbicide or insecticide was applied. The experimental areas were fertilized considering a population density for the forage cactus of 40,000 plants ha^{-1}, with the application of nitrogen-phosphorus-potassium (NPK) doses equal to 200-80-130 kg ha^{-1}.

Irrigation was carried out using a drip system with a flow of 1.57 L h^{-1} at a pressure of 100 kPa and a uniformity coefficient of 92%, with emitters spaced 0.20 m apart. The applied water was classified as high salinity (C3) according to the Richards (1954) classification, with a mean EC of 1.62 dS m^{-1}, a pH of 6.84, a Na^+ concentration of 168.66 mg L^{-1} and a K^+ concentration of 28.17 mg L^{-1}.

In all the experiments, the irrigation was applied three times a week (Mondays, Wednesdays and Fridays), based on 80% of the water requirement (crop evapotranspiration, ET_c) of the forage cactus as this was considered the principal crop in the system. The ET_c was estimated from the product of the reference evapotranspiration (ET_0) and the crop coefficient (K_c), considering K_c equal to 0.52 (Queiroz et al., 2016). In turn, the ETo was obtained daily using the Penman–Monteith equation, which is parameterized by the Food and Agriculture Organization of the United Nation (FAO) (Allen et al., 1998).

During the experimental period, meteorological data were obtained from an automatic weather station of the National Institute of Meteorology (INMET), located approximately 20 m from the experimental areas. Figure 1 shows the behaviour of the rainfall and ET_0 throughout the experimental period (i.e. August 2018 to July 2020). The accumulated rainfall was 1888.80 mm, lower than the ET_0, which had a total value of 3556.81 mm.

2.2.1 | Area 1 (cropping configuration)

Area 1 included different cropping configurations. The plant materials used were three clones of the forage cactus, namely, OEM (*Opuntia stricta* [Haw.] Haw.), IPA Sertânia (IPA, *Nopalea cochenillifera* [L.] Salm-Dyck) and Miúda (MIU, *N. cochenillifera* [L.] Salm-Dyck), and three sorghum cultivars, namely, Progenitor 288 (P.288), SF11 and 467 (*Sorghum bicolor* [L.] Moench).

The forage cactus clones were planted at a spacing of 1.0 × 0.2 m, giving an initial density of 50,000 plants ha^{-1}; the sorghum cultivars were sown in furrows at an initial plant density of 200,000 plants ha^{-1}. The experiment consisted of 15 treatments, arranged in 3 + 3 + 3 × 3 factorial, comprising the three forage cactus clones and the three sorghum cultivars as single crops (SNG) and nine combinations for the cactus–sorghum intercropping system (OEM–SF11, OEM–P.288, OEM–467, IPA–SF11, IPA–P.288, IPA–467, MIU–SF11, MIU–P.288 and MIU–467). Each plot had an area of 20 m^2, comprising four rows of 5 m, with 25 forage cactus plants per row. The working plot was considered the two central rows, disregarding the two plants at each end, with an area equal to 9.20 m^2 $plot^{-1}$ and a total of 46 working plants.

For the present study, the forage cactus clones were in their second crop production cycle, which began in February 2019 and ended in February 2020, totalling ∼400 days of evaluation. Three consecutive sorghum cycles were conducted, including one sowing cycle and two regrowth cycles. Sowing was carried out on 8 February 2019, with the first harvest occurring in June 2019, 110 days after emergence (DAE). In the second cycle, plants were harvested in August 2019, 72 days after cutting (DAC), and in the third cycle, plants were harvested at 82 DAC in November 2019.

The water depth applied in irrigation events throughout the period was 433.3 mm, which was added to the 790.40 mm of rainfall, yielding a total of 1223.7 mm of water received by the plants.

2.2.2 | Area 2 (population density in east–west orientation)

Area 2 consisted of different planting densities of forage cactus in an east–west orientation. In this study, the plant materials used were an OEM clone of the forage cactus (*O. stricta* [Haw.] Haw.) intercropped with the sorghum 467 cultivar (*S. bicolor* [L.] Moench).

The cactus was planted at a fixed spacing of 1 m between rows in an east–west direction, comprising five planting densities, achieved by modifying the spacing between plants (0.10, 0.20, 0.30, 0.40 and 0.50 m), resulting in initial population densities of 100,000, 50,000, 33,333, 25,000 and 20,000 plants ha^{-1}, respectively. Each experimental plot had an area of 12 m^2 and consisted of four planting rows 3 m in length. The working plot consisted of two central rows, and the two plants were discarded at each end.

For the present study, the forage cactus was in its first production cycle, starting in August 2018 and ending in April 2020, giving a total of ∼640 days of cultivation. After planting, the forage cactus remained under no irrigation or intercropping until January 2019, at which time the sorghum was planted and irrigation began. Four consecutive cycles were evaluated in the sorghum crop, including one sowing cycle and three regrowth cycles, with harvesting carried out after grain maturation. The first sorghum cycle had a duration of 115 DAE and was harvested in May 2019; for the second cycle, the harvest was carried out at 84 DAC, with a cut made in August 2019; the third cycle, which had a duration of 99 DAC, was harvested in November 2019; and the fourth and last cycle, which had a duration of 112 DAC, was harvested in March 2020.

The total amount of water received by the system was 1978.9 mm, of which 286.9 mm was from irrigation and 1692.0 mm from rainfall.

2.2.3 | Area 3 (population density in north–south orientation)

Area 3 followed the same treatments as did Area 2; however, they differed in terms of their planting orientation, which was in a north–south direction. The OEM clone (*O. stricta* [Haw.] Haw.) was again intercropped with sorghum 467 (*S. bicolor* [L.] Moench).

The amount of water applied via irrigation during the experimental period was equal to 294.6 mm, with rainfall equal to 1692.0 mm, resulting in a total of 1986.6 mm of water input to the system.

2.2.4 | Area 4 (population density of cactus and sorghum)

This area consisted of different population densities of forage cactus and sorghum, obtained by changing the spacing between rows. The plant materials used were the OEM clone (*O. stricta* [Haw.] Haw.) intercropped with the sorghum 467 cultivar (*S. bicolor* [L.] Moench).

The forage cactus was planted at a fixed spacing of 0.20 m between plants, with variations in the spacing between rows of 1.00, 1.25, 1.50 and 1.75 m, which comprised the treatments and resulted in initial planting densities of 50,000, 40,000, 33,333 and 28,571 plants ha^{-1}, respectively, for the forage cactus and 200,000, 160,000, 133,333 and 114,285 plants ha^{-1}, respectively, for the sorghum.

The duration of the four sorghum cycles, as well as the forage cactus cycle, was the same as that described for experimental Area 2. The water received by the system during the experimental period via irrigation was 283.1 mm, which was added to 1692.0 mm of rainfall for a total of 1975.1 mm.

2.3 | Biometric variables

In the cactus, monthly biometric and biomass campaigns were carried out every 90 days to quantify the structural aspects necessary to determine the morphophysiological indices, delimit the phenological phases and establish the cutting time of the crop. Biometric evaluations were carried out on one plant per plot by measuring plant height (PH, cm; distance from the ground to the highest cladode of the plant), plant width (PW, cm; horizontal distance between the furthest cladodes), total number of cladodes per plant (TNC, units) and the number of cladodes in order of appearance (NC1, NC2, etc.). The cladode length (CL, cm), cladode width (CW, cm), cladode perimeter (CP, cm) and cladode thickness (CT, cm) on one representative branch were quantified. Furthermore, as per the model proposed by Silva et al. (2014b), the cladode area (CA, cm^2) was determined by the order of appearance and clone (Equations 1, 2 and 3). The cladode area index (CAI, m^2 m^{-2}) was then calculated from the ratio between the CA and the adopted spacing using Equation 4 (Pinheiro et al., 2014):

$$CA_{IPA} = 1.6691 \times \frac{(1 - \exp(0.0243 \times CP)}{-0.0243}, \quad (1)$$

$$CA_{MIU} = 0.7198 \times CL \times CW, \quad (2)$$

$$CA_{OEM} = 0.7086 \times \frac{(1 - \exp(-0.000045765 \times CL \times CW)}{0.000045765}, \quad (3)$$

$$CAI = \frac{\frac{\left(\sum_{n}^{i=1} CA\right)}{10000}}{S1 \times S2}, \quad (4)$$

where CA = cladode area (cm^2); CP = cladode perimeter (cm); CL = cladode length (cm); CL = cladode width (cm); CAI = cladode area index (m^2 m^{-2}); 10,000 = conversion factor from cm^2 to m^2; S1 = spacing between rows (m); and S2 = spacing between plants (m).

The fresh and dry biomass (Mg ha^{-1}) were determined by choosing one representative plant per plot, which was harvested and weighed, leaving only the basal cladodes in the field. Two cladodes representing the middle third of the plant were chosen, weighed on a balance (fresh matter), broken up, packed in identified paper bags and placed in a forced air circulation oven at 55°C to constant weight. The dry matter content was obtained considering the fresh and dry matter of the cladodes. The fresh matter yield (Mg ha^{-1}) was estimated from the total fresh weight and final plant density in the working plots. The dry matter yield (Mg ha^{-1}) was estimated considering the dry matter content of the cladodes and the estimated values of the fresh matter of the plants.

Biometric measurements of the sorghum plants were taken weekly on two plants per plot. For each plant, the number of live leaves (NLL, units) and the leaf width (LW + 3, cm) and leaf length (LL + 3, cm) of the +3 leaves were determined. The leaf area (LA, cm^2) was estimated according to Equation 5 (Shih et al., 1981). The leaf area index (LAI, cm^2 cm^{-2}) was estimated using Equation 6:

$$LA = 0.741 \times LL + 3 \times LW + 3, \quad (5)$$

$$LAI = \frac{(LA \times NLL)}{(S1 \times S2)}, \quad (6)$$

where LA = leaf area (cm^2); LL + 3 = length of the +3 leaf (cm); LW + 3 = width of the +3 leaf (cm); LAI = leaf area index (cm^2 cm^{-2}); NLL = number of live leaves (units); S1 = spacing between rows (cm); and S2 = spacing between plants (cm).

The fresh and dry sorghum biomass (Mg ha^{-1}) was determined by sampling every 15 days until the final harvest was carried out, which was carried out when the grain reached physiological maturity. One representative plant per plot was chosen, divided into live leaves, dead leaves, stalks and panicles, weighed (fresh matter), packed in properly identified paper bags and then placed in a forced air circulation oven at 55°C to constant weight (dry matter).

2.4 | Morphophysiological indices of forage cactus and sorghum

The morphophysiological indices were obtained by analysing sigmoid regressions, relating the values for plant dry matter (PDM), leaf dry matter (LDM), CAI and LAI with the accumulated degree days (ADD, °Cday). The ADD was obtained by summing the values for degree days (DD, °Cday), which was calculated from the difference between the mean temperature for each day and a base temperature for the forage cactus of 22°C (Araújo Júnior et al., 2021b) and sorghum of 10.8°C (Bandeira et al., 2016). The sigmoid models that had a coefficient of determination (R^2) greater than 0.85 were derived to calculate the daily rates of dry matter accumulation, resulting in the AGR of each crop (Mg ha^{-1} °Cday). In addition to the AGR, NAR (Mg ha^{-1} °Cday), RGR (Mg Mg^{-1} °Cday) and SCA (ha Mg^{-1}) were calculated for the cactus. For sorghum, in addition to the NAR and RGR, the SLA (ha Mg^{-1}), LAR (ha Mg^{-1}) and LMR (Mg Mg^{-1}) were calculated. The calculations were carried out based on the following ratios: NAR = AGR/CAI, RGR = AGR/PDM, SCA = CAI/PDM, SLA = ILA/LDM, LAR = LAI/PDM and LMR = LDM/PDM.

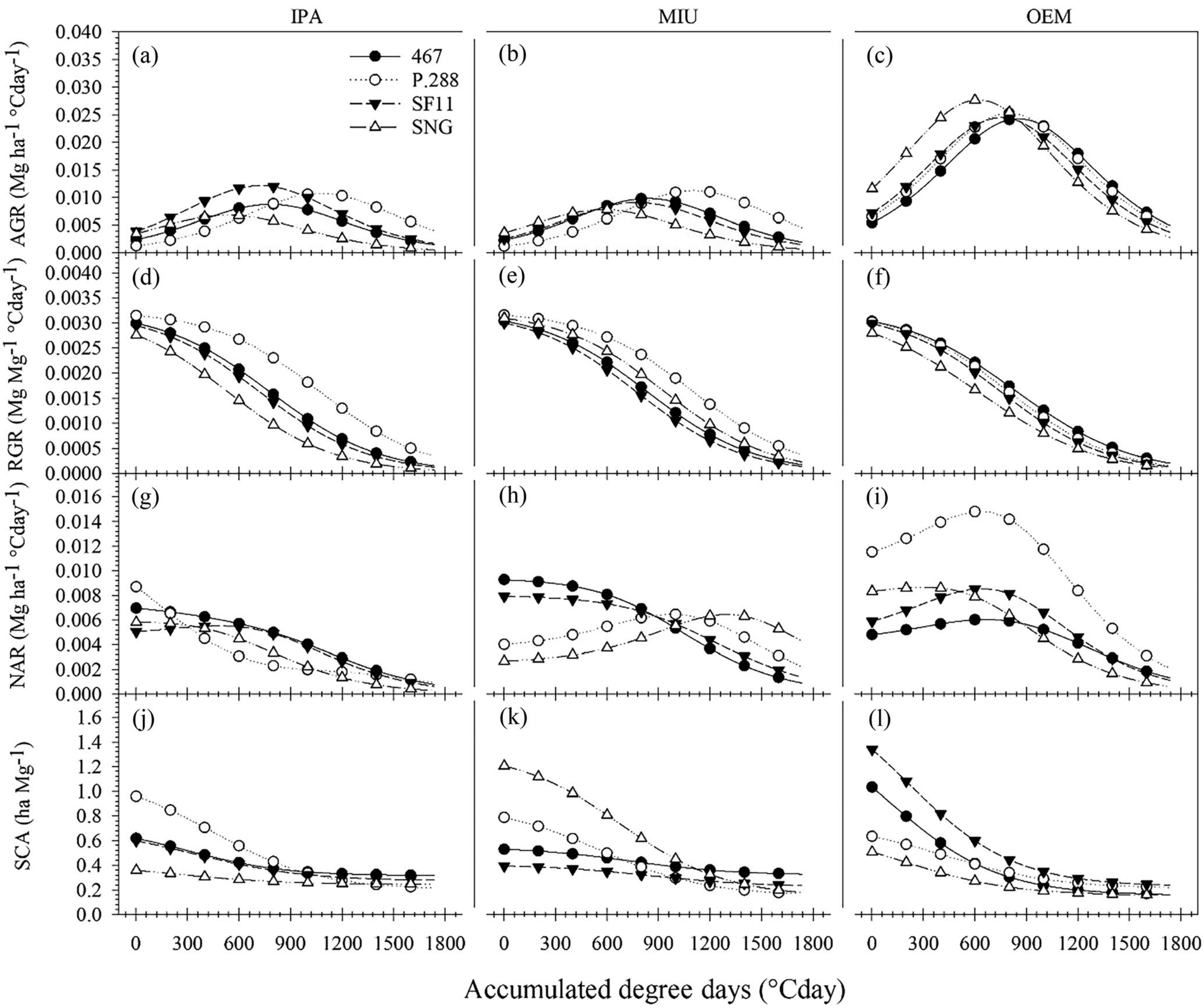

FIGURE 2 Morphophysiological indices of forage cactus clones (IPA, IPA Sertânia; MIU, Miúda; OEM, Orelha de Elefante Mexicana) as single crops (SNG) and intercropped with sorghum cultivars (467; SF11; P.288, Progenitor 288). AGR, absolute growth rate (A, B, C); RGR, relative growth rate (D, E, F); NAR, net assimilation rate (G, H, I); SCA, specific cladode area (J, K, L).

2.5 | Phenophase and cutting time in forage cactus

The phenological delimitation was determined by regression analysis using sigmoid models with three parameters, relating the ADD (°Cday) to the number of cladodes in order of appearance (first order, second order, etc.). Equations with R^2 greater than 0.90 and with significant parameters ($p < 0.05$) were derived to obtain the daily rate of cladode emission. An advance in the phenological phase was considered whenever the emission of higher-order cladodes was greater than the emission of lower-order cladodes (Amorim et al., 2017).

In turn, the cutting time was determined based on the dry matter accumulation values. For this purpose, the ADD that showed 25% of the maximum rate of dry matter accumulation was defined as the ideal cutting time for the forage cactus, as per the methodology described by Amorim et al. (2017).

2.6 | Statistical analysis

The three-parameter sigmoid regression models used to obtain morphophysiological indices, delimit the phenophases and determine the rate of dry matter accumulation were adjusted using the significance of the model ($p < 0.05$) and R^2 greater than 0.85. All the adjustments were carried out using SigmaPlot v 14.0 software from Systat Software (San Jose, California, USA).

3 | RESULTS

3.1 | Morphophysiological indices of forage cactus and sorghum

3.1.1 | Forage cactus clones

Figure 2 shows the morphophysiological indices of forage cactus clones intercropped with sorghum cultivars, as well as those of the monocropped cactus. A difference in behaviour can be seen between the clones under study due to the imposed treatments. The AGR (Figure 2A, B and C) showed two well-defined phases for each clone, regardless of treatment, one with an increase in dry matter accumulation (IPA ~ 787 °Cday; MIU ~ 854 °Cday; OEM ~ 762 °Cday) closely followed by a reduction. In general, the highest values were found for the OEM clone compared to the IPA and MIU clones. Among the systems that included the OEM clone, OEM-SNG had the highest value, with a maximum rate equal to 0.027 Mg ha^{-1} °Cday^{-1} at 620 °Cday (155 days). The other OEM configurations had a mean value of 0.024 Mg ha^{-1} °Cday^{-1}, which occurred at 816 °Cday (204 days). The mean value for the configurations that included the IPA and MIU clones was 0.009 Mg ha^{-1} °Cday^{-1} at 821 °Cday (205 days); however, for the same clones, the configurations that included the P.288 cultivar presented a delayed peak compared to the other configurations, with mean values of 0.009 and 0.010 Mg ha^{-1} °Cday^{-1} for the IPA and MIU clones, respectively, which occurred at 1023 °Cday (255 days).

For the RGR (Figure 2D, E and F), it can be seen that the forage cactus clones, regardless of the cropping configuration, showed a reduction in value over time, with higher values at the start of the cycle. The highest value was achieved with the MIU–P.288 configuration, with 0.0032 Mg Mg ha^{-1} °Cday^{-1} occurring at the beginning of the cycle.

In the case of the NAR (Figure 2G, H and I), the forage cactus clones submitted to different configurations showed different behaviours; however, they all showed a reduction during the final phase of the cycle. The greatest value was obtained with the OEM–P.288 configuration, with a maximum value of 0.014 Mg ha^{-1} °Cday^{-1} at 623 °Cday (156 days).

For the SCA (Figure 2J, K and 2 L), the maximum value for each configuration was observed during the initial phase of the cycle, with a marked reduction over time. The configuration that included the OEM clone intercropped with the SF11 sorghum cultivar had the highest value for this index, 1.34 ha Mg^{-1}, which was observed during the initial phase of the experimental period.

When grown in an east–west orientation under different planting densities, the behaviour of the morphophysiological indices of the forage cactus intercropped with sorghum 467 varied as a function of density (Figure 3).

Evaluating the AGR (Figure 3A), it was found that at the highest planting density (100,000 plants ha^{-1}), the forage cactus showed higher values, with a maximum value of 0.028 Mg ha^{-1} °Cday^{-1} at 1316 °Cday (329 days). In the case of the RGR (Figure 3B), at all densities, higher values were observed during the initial phase of cultivation, with a gradual reduction as the crop grew, with the highest value occurring at the lowest planting density (20,000 plants ha^{-1}), which was equal to 0.0024 Mg Mg^{-1} °Cday^{-1}. For NAR (Figure 3C), the cactus showed different behaviours under different densities, with maximum values at the two highest densities of 0.033 Mg ha^{-1} °Cday^{-1} for 50,000 plants ha^{-1} and 0.028 Mg ha^{-1} °Cday^{-1} for 100,000 plants ha^{-1} occurring at 307 and 461 °Cday, respectively (~76 and 115 days). The SCA reached a maximum for all treatments at the start of the cycle, decreased throughout the cycle and stabilized at 2000 °Cday (500 days).

The forage cactus plants under an intercropping system with sorghum 467 in a north–south orientation showed different behaviours in relation to the different planting densities (Figure 4).

The highest values for AGR (Figure 4A) were found when the forage cactus was grown at the highest planting density, with values of 0.028 Mg ha^{-1} °Cday^{-1} at a planting density of 50,000 plants ha^{-1} occurring at 1873 °Cday (~468 days), followed by a density of 100,000 plants ha^{-1}, with a maximum value of 0.027 Mg ha^{-1} °Cday^{-1} at 1532 °Cday (~383 days). The behaviour of the RGR (Figure 4B) was similar to that when the crop was grown in an east–west orientation; however, the highest values were observed at a density of 50,000 plants ha^{-1}, with a value of 0.0029 Mg Mg^{-1} °Cday^{-1} at the start of cultivation. For the NAR index (Figure 4C), the density of 100,000 plants ha^{-1} afforded the highest rate, with a maximum of 0.024 Mg ha^{-1} °Cday^{-1} at 1100 °Cday (275 days). The SCA (Figure 4D) showed similar behaviour at all densities, with maximum values during the initial phase and a gradual reduction as the crop grew and accumulated thermal energy, reaching a constant value after approximately 1,600 °Cday (400 days). The highest values were observed at the highest planting densities (50,000 and 100,000 plants ha^{-1}), with a mean maximum value of 1.9 ha Mg^{-1}.

The different planting densities resulting from changing the spacing between rows promoted differences in the morphophysiological indices (Figure 5). The highest density (50,000 plants ha^{-1}) afforded the maximum value for the AGR (Figure 5A), 0.032 Mg ha^{-1} °Cday^{-1} at

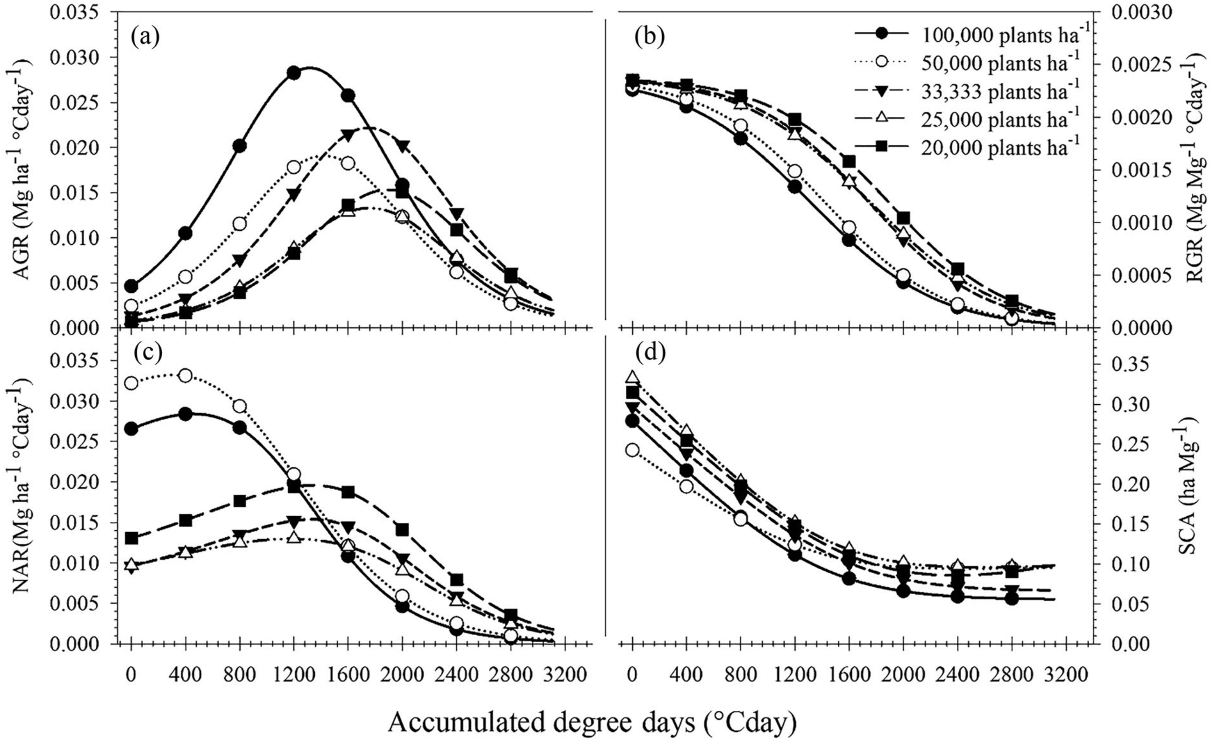

FIGURE 3 Morphophysiological indices of forage cactus grown in east–west orientation intercropped with sorghum under different planting densities. AGR, absolute growth rate (A); RGR, relative growth rate (B); NAR, net assimilation rate (C); SCA, specific cladode area (D).

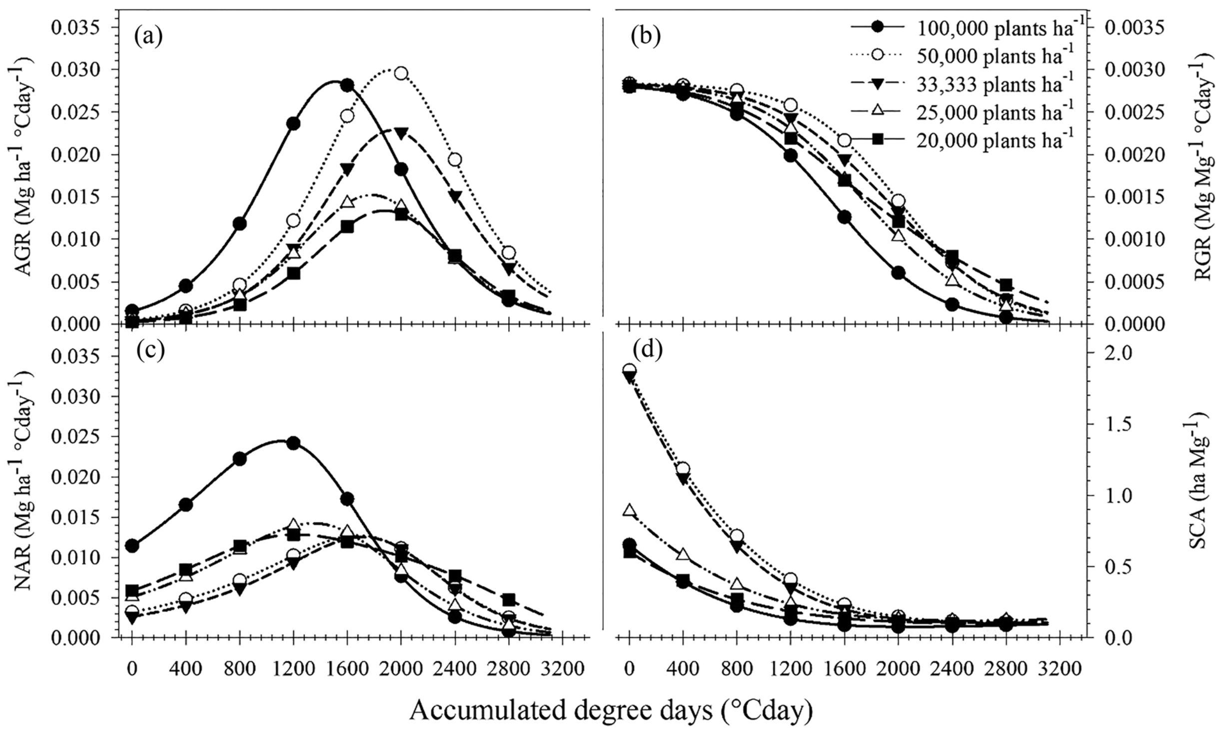

FIGURE 4 Morphophysiological indices of forage cactus grown in north–south orientation intercropped with sorghum under different planting densities. AGR, absolute growth rate (A); RGR, relative growth rate (B); NAR, net assimilation rate (C); SCA, specific cladode area (D).

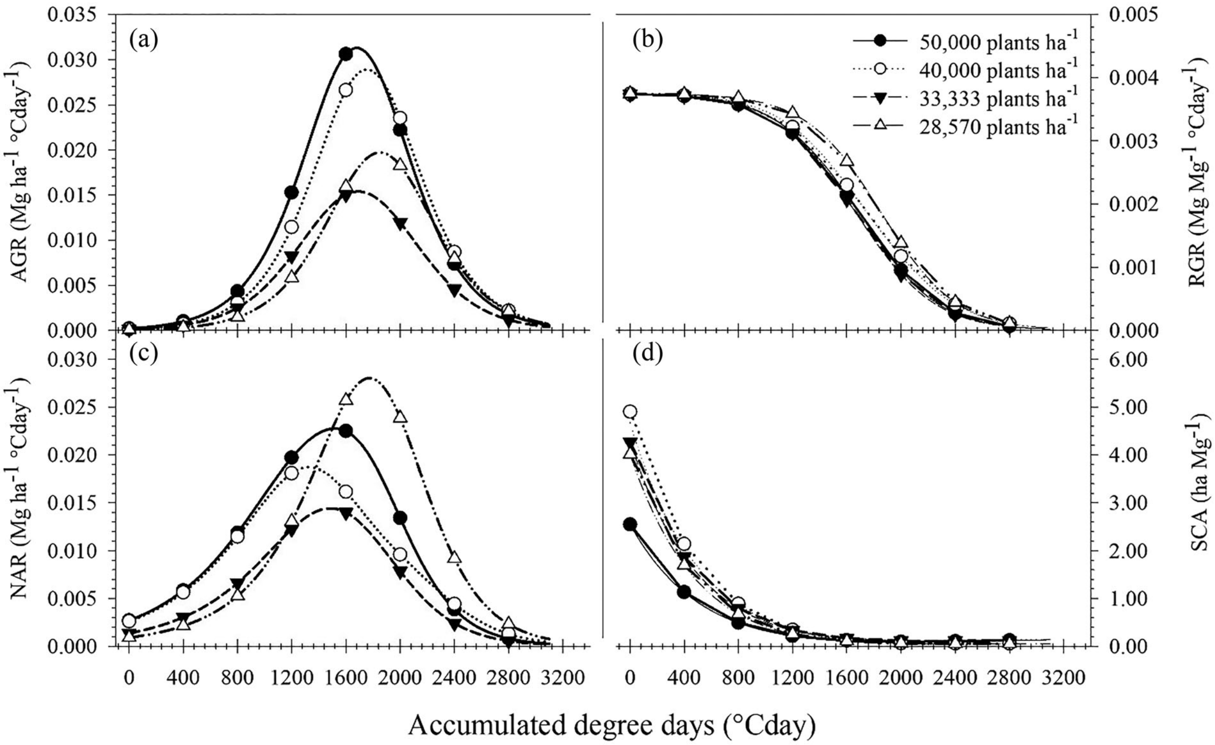

FIGURE 5 Morphophysiological indices of forage cactus intercropped with sorghum under different planting densities and different spacing between rows. AGR, absolute growth rate (A); RGR, relative growth rate (B); NAR, net assimilation rate (C); SCA, specific cladode area (D).

1680 °Cday (420 days). For the RGR (Figure 5B), the behaviour was similar at all the applied densities, with higher values at the start of the cycle, remaining constant up to approximately 780 °Cday (195 days), followed by a gradual decrease. Compared to the other planting densities, the lowest density (28,570 plants ha^{-1}) promoted greater NAR values (Figure 5C), occurring at 1718 °Cday (430 days), with a mean value of 0.027 Mg ha^{-1} $°Cday^{-1}$. For the SCA, the highest values were found during the initial phase, with an emphasis on the density of 40,000 plants ha^{-1}, which achieved a higher value than the other densities of 5 ha Mg^{-1} $°Cday^{-1}$. However, this behaviour was similar at all densities, stabilizing at approximately 1,500 °C (375 days).

3.1.2 | Sorghum cultivars

The behaviour of the morphophysiological rates varied for the different sorghum cultivars depending on the cropping configuration and crop cycle (Figure 6). The growth rate of the crop (AGR; Figure 6A, B and C) had three well-defined phases for the three crop cycles and configurations: First, dry matter accumulation was slow (Cycle 1—605 °Cday; Cycle 2—105 °Cday; Cycle 3—350 °Cday), followed by the second phase characterized by rapid growth and then the third phase characterized by a reduction in values (Cycle 1—1,-420 °Cday; Cycle 2—725 °Cday; Cycle 3—980 °Cday); the highest values were observed for the configurations including the 467 and P.288 cultivars. Evaluating the cycles, it was found that as the cycles continued, regardless of the configuration, there was a reduction in the rates. For the RGR (Figure 6D, E and F), the maximum rate was observed during the initial phase of each cycle, with a decrease at approximately 900, 420 and 600 °Cday (56, 26 and 37 days), for Cycles 1, 2 and 3, respectively. NAR (Figure 6G, H and I) showed two well-defined phases, the first with a gradual increase in values (Cycle 1—1,386 °Cday; Cycle 2—594 °Cday; Cycle 3—822-°Cday) and the second, shortly after, showing a reduction.

The SLA showed different behaviour in relation to Cycle 1 than to the other cycles (Figure 6J, K and L). During the first cycle, there was a gradual increase in value, mainly for the 467–MIU and 467–OEM configurations, with a decrease in value at approximately 980 °Cday (61 days); in contrast, Cycles 2 and 3 showed similar behaviour, characterized by a continuous reduction in value. The LAR (Figure 6M, N and O) for Cycles 1 and 2 showed an increasing trend during the initial phase of the cycle, with a reduction at 430 °Cday (27 days); in the

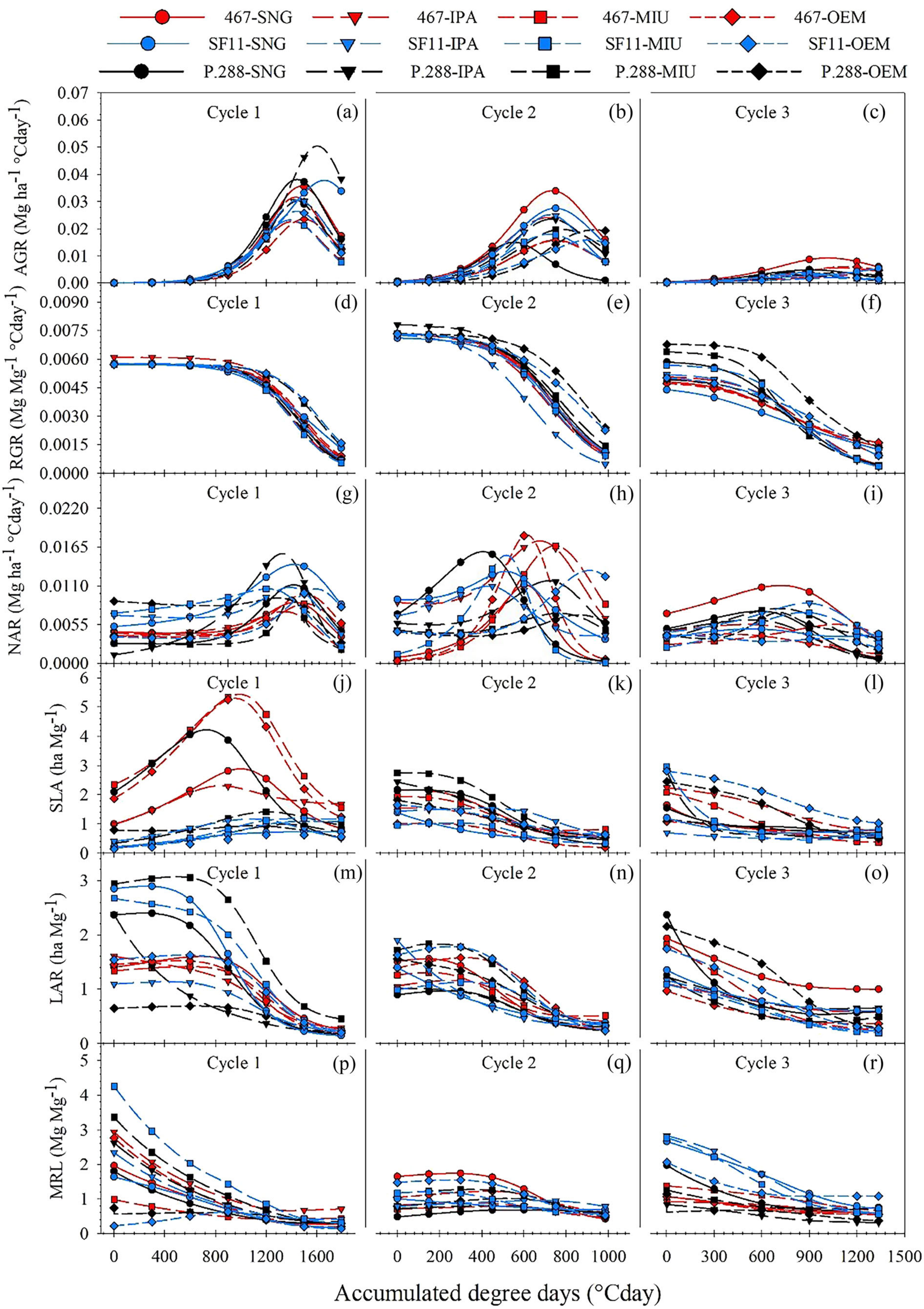

FIGURE 6 Legend on next page.

FIGURE 6 Morphophysiological indices during three sorghum cycles (cultivars 467, SF11 and P.288) under different cropping configurations. AGR, absolute growth rate (A, B and C); RGR, relative growth rate (D, E and F); NAR, net assimilation rate (G, H and I); SLA, specific leaf area (J, K and L); LAR, leaf area ratio (M, N and O); LMR, leaf mass ratio (P, Q and R). IPA, IPA Sertânia; MIU, Miúda; OEM, Orelha de Elefante Mexicana; SNG, single crop.

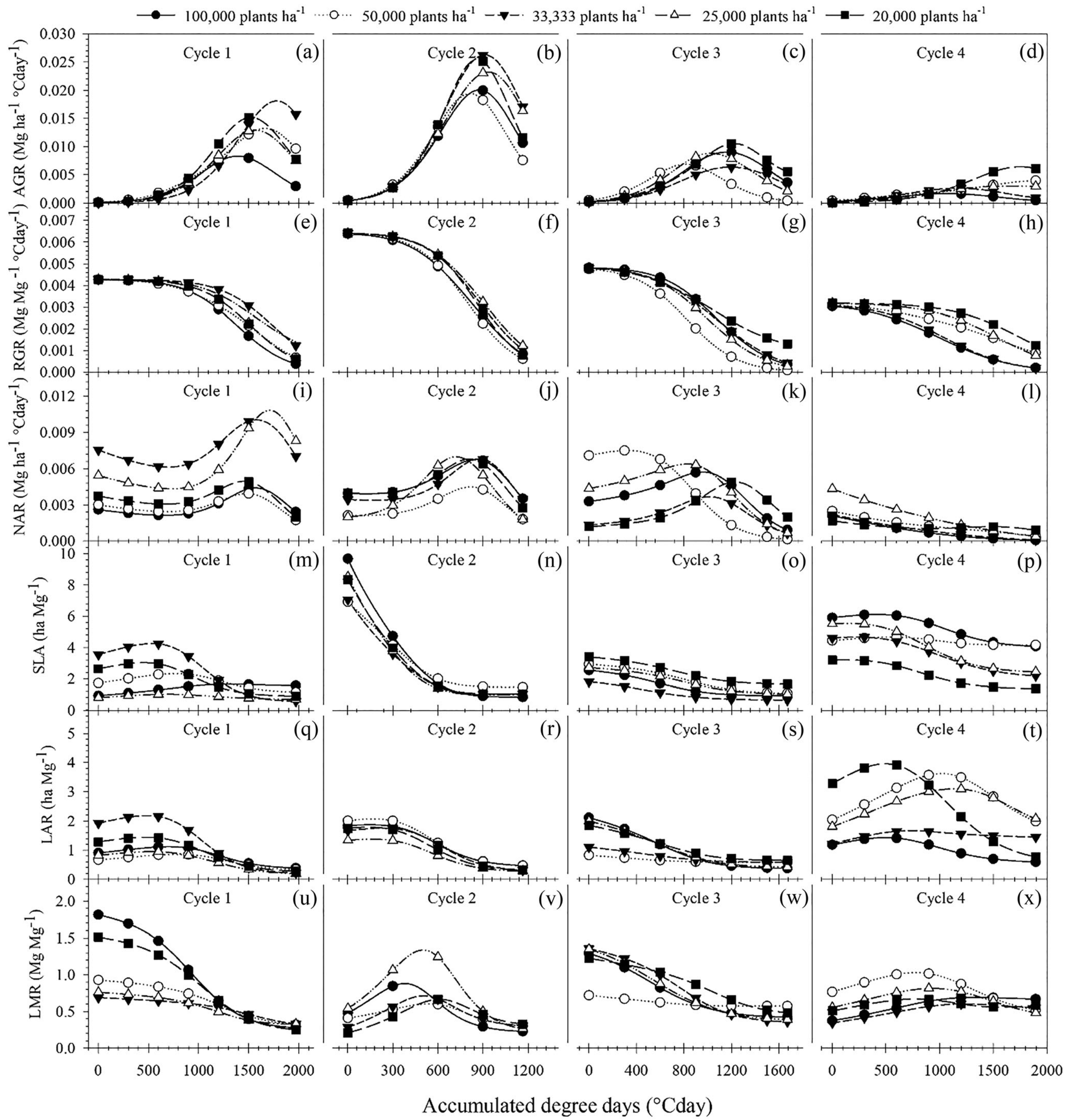

FIGURE 7 Morphophysiological indices during four sorghum cycles in east–west orientation intercropped with forage cactus under different planting densities. AGR, absolute growth rate (A, B, C and D); RGR, relative growth rate (E, F, G and H); NAR, net assimilation rate (I, J, K and L); SLA, specific leaf area (M, N, O and P); LAR, leaf area ratio (Q, R, S and T); LMR, leaf mass ratio (U, V, W and X).

case of Cycle 3, the behaviour showed a continuous reduction in value from the start of the cycle. For the LMR (Figure 6P, Q and R), there was a reduction in value throughout Cycles 1 and 3, while for Cycle 2, the values remained constant up to 420 °Cday (26 days), decreasing shortly after.

When sorghum was intercropped with forage cactus grown in an east–west orientation, the indices varied as a function of the crop cycle, with similar behaviour between the different density treatments applied to the forage cactus (Figure 7). The AGR (Figure 7A, B, C and D) showed three well-defined phases, where the first

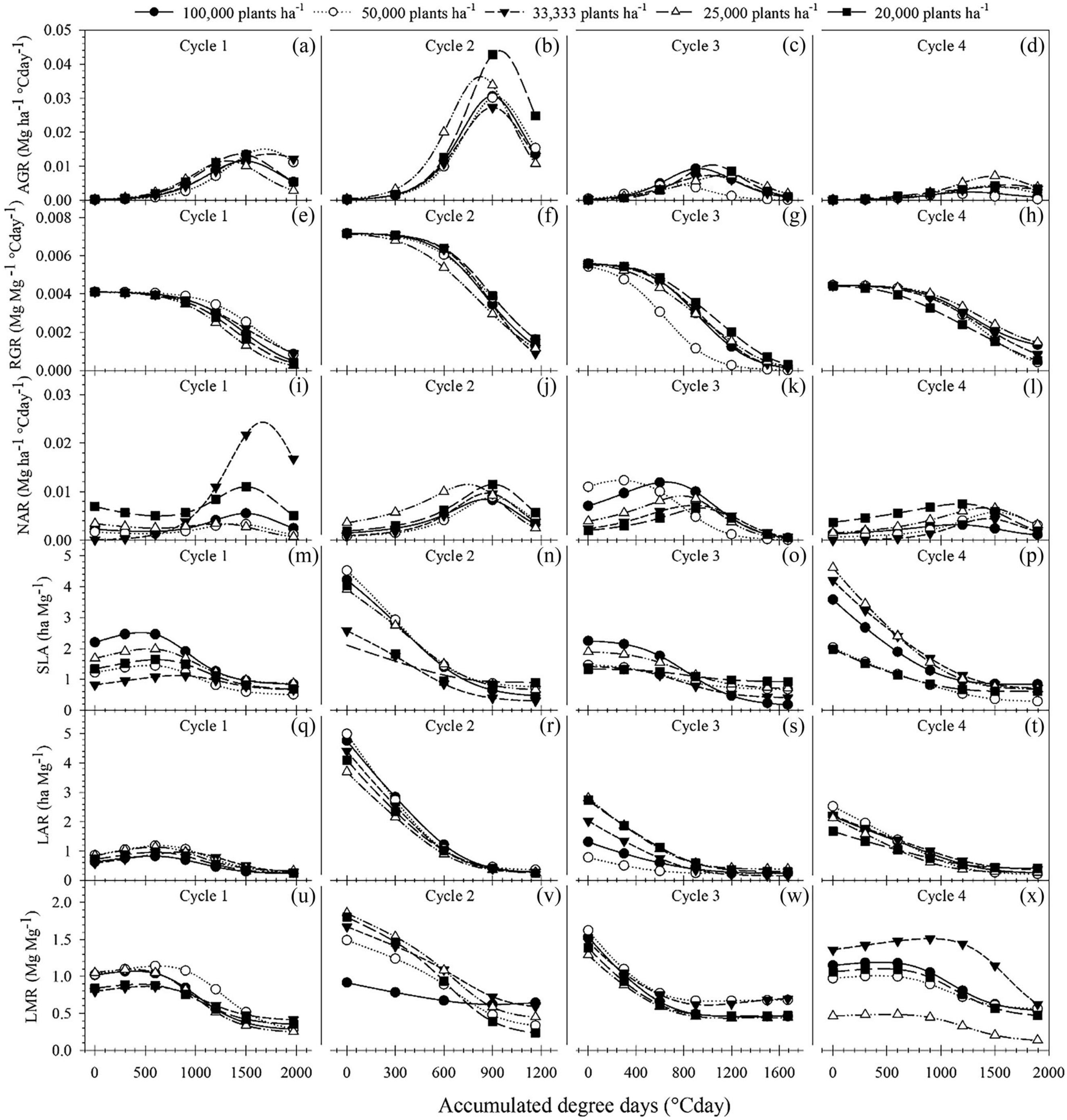

FIGURE 8 Morphophysiological indices during four sorghum cycles in north–south orientation in intercropping system with forage cactus under different planting densities. AGR, absolute growth rate (A, B, C and D); RGR, relative growth rate (E, F, G and H); NAR, net assimilation rate (I, J, K and L); SLA, specific leaf area (M, N, O and P); LAR, leaf area ratio (Q, R, S and T); LMR, leaf mass ratio (U, V, W and X).

phase was characterized by the slow accumulation of dry matter (Cycle 1—510 °Cday; Cycle 2—285 °Cday; Cycle 3—278 °Cday; Cycle 4—475 °Cday); the second, shortly after, represented by rapid accumulation; and the third by a reduction in value (Cycle 1—1,504 °Cday; Cycle 2—880 °Cday; Cycle 3—1,200 °Cday; Cycle 4—1,450 °Cday).

The highest values of RGR (Figure 7E, F, G and H) were found during the initial phase of the crop, with a reduction in value after 880 °C day for Cycle 1, 352 °C day for Cycle 2, 446 °C day for Cycle 3 and 612 for Cycle 4, with similar trends for each treatment. The first three cycles showed an initial increase in NAR (Figure 7I, J, K and

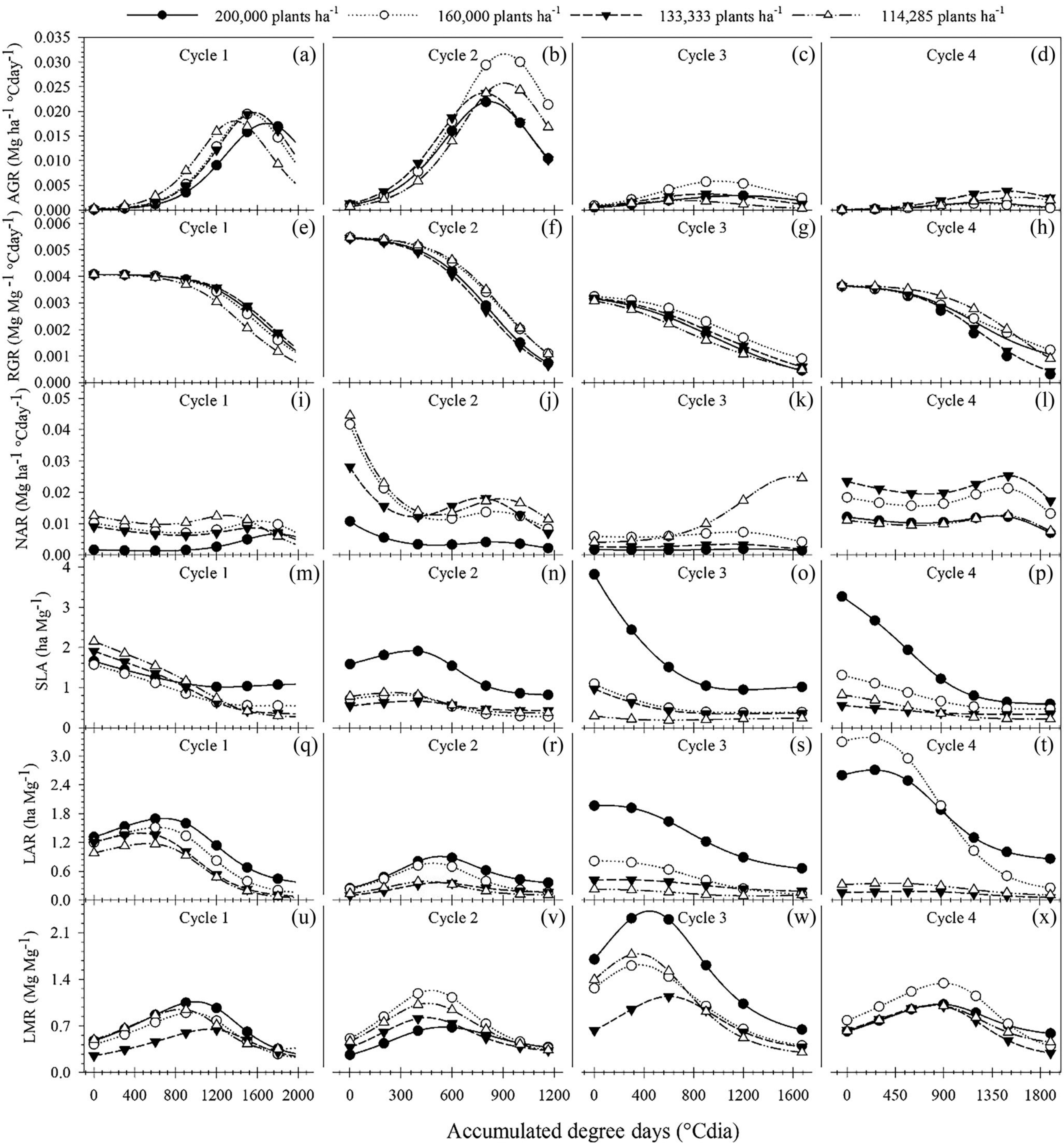

FIGURE 9 Morphophysiological indices during four sorghum cycles intercropped with forage cactus under different planting densities. AGR, absolute growth rate (A, B, C and D); RGR, relative growth rate (E, F, G and H); NAR, net assimilation rate (I, J, K and L); SLA, specific leaf area (M, N, O and P); LAR, leaf area ratio (Q, R, S and T); LMR, leaf mass ratio (U, V, W and X).

L), with a gradual reduction immediately following the peak; on the other hand, the fourth cycle was characterized by a continuous reduction in NAR throughout the period. The SLA (Figures 7M, 7 N, 7O and 7P) showed different behaviours for the different cycles under evaluation, with an initial increase in value for Cycle 1 and a decrease at approximately 700 °Cday (44 days), in contrast to the other cycles with a gradual reduction in value from the start of each cycle. The LAR (Figure 7Q, R, S and T) and LMR (Figures 7U, 7 V, 7 W and 7X) showed similar behaviour, with Cycles 1, 2 and 4 showing an increasing trend in value, with a gradual reduction soon after 607 °Cday, 417 °Cday and 592 °Cday, respectively. Cycle 3 showed a continuous decrease starting from the initial phase of the cycle.

The morphophysiological indices for sorghum grown intercropped with forage cactus in a north–south orientation (Figure 8) showed similar behaviour to that found under the east–west orientation described above, with a difference in the observed values. The values, therefore, vary depending on the cycle under evaluation and the treatments imposed, where it was found that the highest values of most variables were observed during the second cycle.

Figure 9 shows the behaviour of the morphophysiological indices of the four sorghum cycles intercropped with forage cactus under changes in population density. Within each cycle, the behaviour of the indices was similar to that of the densities under evaluation. In general, the behaviour of the indices was similar to that seen in

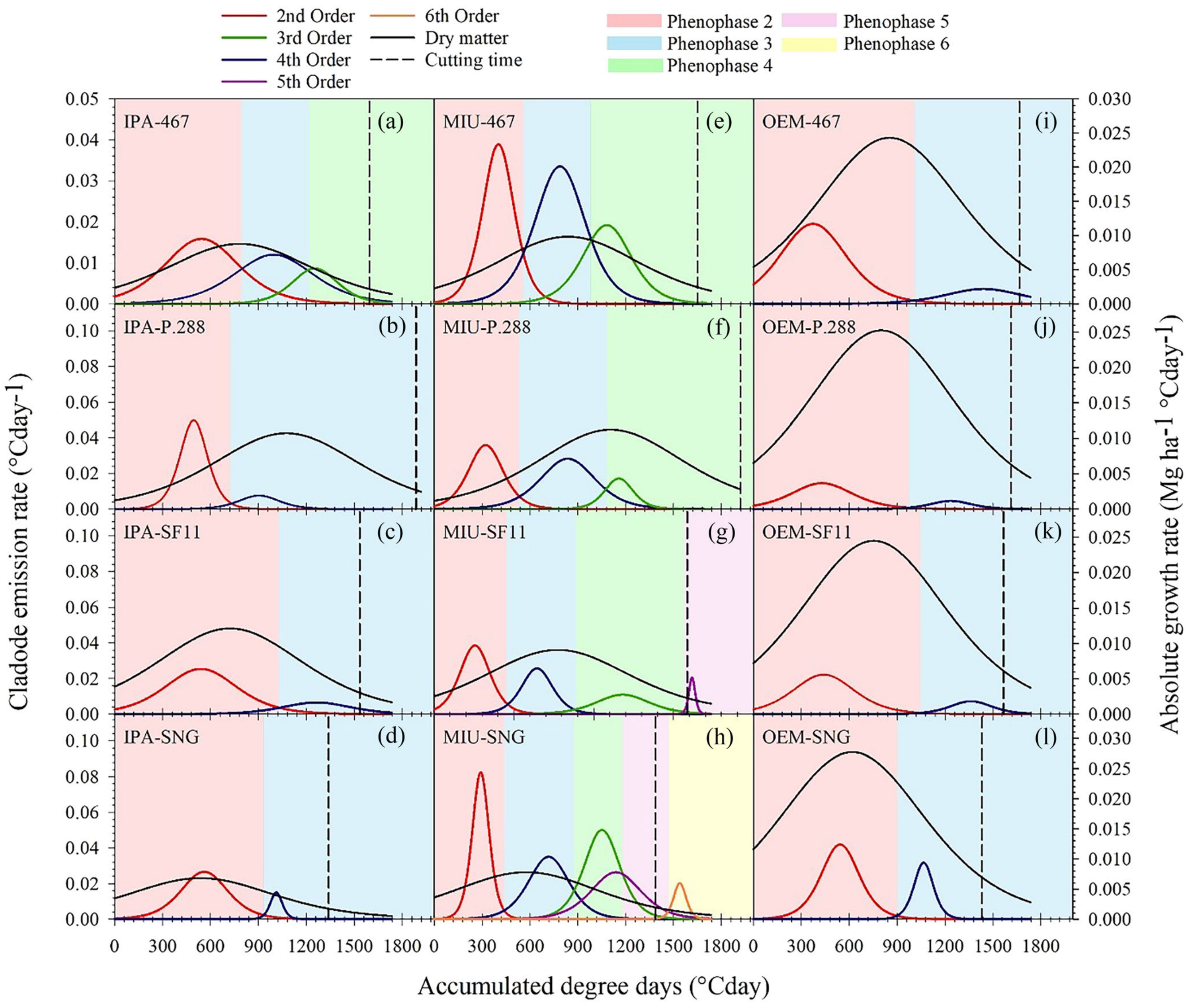

FIGURE 10 Plant phenophase and cutting time in forage cactus clones (IPA, IPA Sertânia; MIU, Miúda; OEM, Orelha de Elefante Mexicana) in single crop (SNG) and intercropped with sorghum cultivars (467, IP; SF11; P.288, Progenitor 288) for accumulated degree days (ADD, °Cday).

Experimental Areas 2 and 3, with differences in the values obtained for the evaluated rates. According to the SLA, LAR and LMR indices, the highest density (200,000 plants ha^{-1}) promoted the highest values in each of the cycles, except for LAR Cycle 4 and LMR Cycles 2 and 4, where the highest values were found at a density of 160,000 plants ha^{-1}.

3.2 | Phenophase and cutting time in forage cactus

Figure 10 shows that the number and duration of the phenophases in the forage cactus, as well as the rate of dry matter accumulation and ideal cutting time based on the ADD, vary with changes in cropping configuration. However, regardless of the configuration used, the rate of second-order cladode emission was greater than the other rates.

Phenophases 2 and 3 occurred in all configurations, characterized by the emission of secondary and tertiary cladodes, respectively. The variation in both the duration and maximum rate of emissions was due to the forage cactus clone used and the cropping system to which it was subjected. Phenophase 4 (i.e. fourth-order cladode emission) was observed in all configurations containing the MIU clone (Figure 10E, F, G and H) and in the IPA–467 configuration (Figure 10A). In turn, the occurrence of more advanced phenophases was observed only in configurations that included the MIU clone. Phenophase 5, represented by the emission of fifth-order cladodes, was observed in the MIU–SF11 and MIU–SNG configurations (Figure 10G and H), while Phenophase 6, defined by the emission of sixth-order cladodes, was observed only in the MIU-SNG configuration (Figure 10H).

The duration of the second phase was longer when the configuration included the OEM clone (Figure 10I, J, K and L), with a mean duration of approximately 995 °Cday (~249 days), followed by the configurations with the IPA clone (~874 °Cday, 219 days), while the shortest duration was seen in the configurations with the MIU clone, with an average duration of 500 °Cday (~125 days).

Regarding the cutting time, dry matter accumulation varied depending on the clone and configuration used (Figure 10). In general, configurations that included the OEM clone showed the highest rates of dry matter accumulation (Figure 10I, J, K and L), with a mean of 0.025 Mg ha^{-1} °$Cday^{-1}$, and the maximum accumulation occurred on average at 785 °Cday (~196 days). For all clones, the configuration that included the P.288 sorghum cultivar (Figure 10B, F and J) resulted in a greater need for thermal accumulation (average of ~1803 °Cday, 450 days) to carry out harvesting, that is, a delay in harvesting the forage cactus. On the other hand, when the clones were cultivated on single crops (Figure 10D, H and L), the cutting time increased compared to that of the other treatments, with cutting carried out at 1387 °C on average (~346 days).

Another factor that influenced the variation in the number and duration of phenophases in the forage cactus, together with dry matter accumulation and cutting time, was planting density (Figures 11, 12 and 13).

The cactus cultivated under different densities in an east–west orientation (Figure 11) exhibited Phenophases 1, 2 and 3 at all densities, defined as the emission of first-, second- and third-order cladodes, respectively. Phenophase 4, characterized by the emission of fourth-order cladodes, was detected at densities of 33,333, 25,000 and 20,000 plants ha^{-1}. However, the maximum rate of fourth-order cladode emission was greater than the other rates at the lowest planting density (20,000 plants ha^{-1}).

On the other hand, the maximum rate of dry matter accumulation was found at the highest planting density (Figure 11A; 100,000 plants ha^{-1}), with a value of 0.030 Mg ha^{-1} °$Cday^{-1}$, occurring at 1350 °Cday (~337 days). The higher planting density (Figure 11A; 100,000 plants ha^{-1}) also favoured anticipation of the cutting time, and harvesting could be carried out at 2424 °Cday (606 days), while the lowest density (Figure 11E; 20,000 plants ha^{-1}) resulted in a delay in the forage cactus harvest, with the cut at 3000 °Cday (750 days).

For the cactus plants grown in a north–south orientation and subjected to different planting densities (Figure 12), the behaviour was similar to that observed in the east–west orientation (Figure 11), with differences in the number and duration of the phenophases that occurred.

As such, under the north–south orientation, the forage cactus presented Phenophase 4 only at densities of 25,000 and 20,000 plants ha^{-1} (Figure 12D and E), with a longer duration (773 °Cday—193 days) at the lowest density under study (Figure 8E; 20,000 plants ha^{-1}).

The maximum rate of dry matter accumulation was found at densities of 100,000 and 50,000 plants ha^{-1} (Figure 12A and B), with a mean value of 0.030 Mg ha^{-1} °$Cday^{-1}$ occurring at 1500 and 1700 °Cday (375 and 425 days), respectively. As in the east–west orientation, the highest density (Figure 12A) anticipated crop harvest, with a delay at the lowest density (Figure 12E), while cuts occurred at 2846 and 2,945 °Cday (711 and 736 days), respectively.

Figure 13 shows the number and duration of phenophases, together with the rate of dry matter accumulation and cutting time, in forage cactus plants grown at

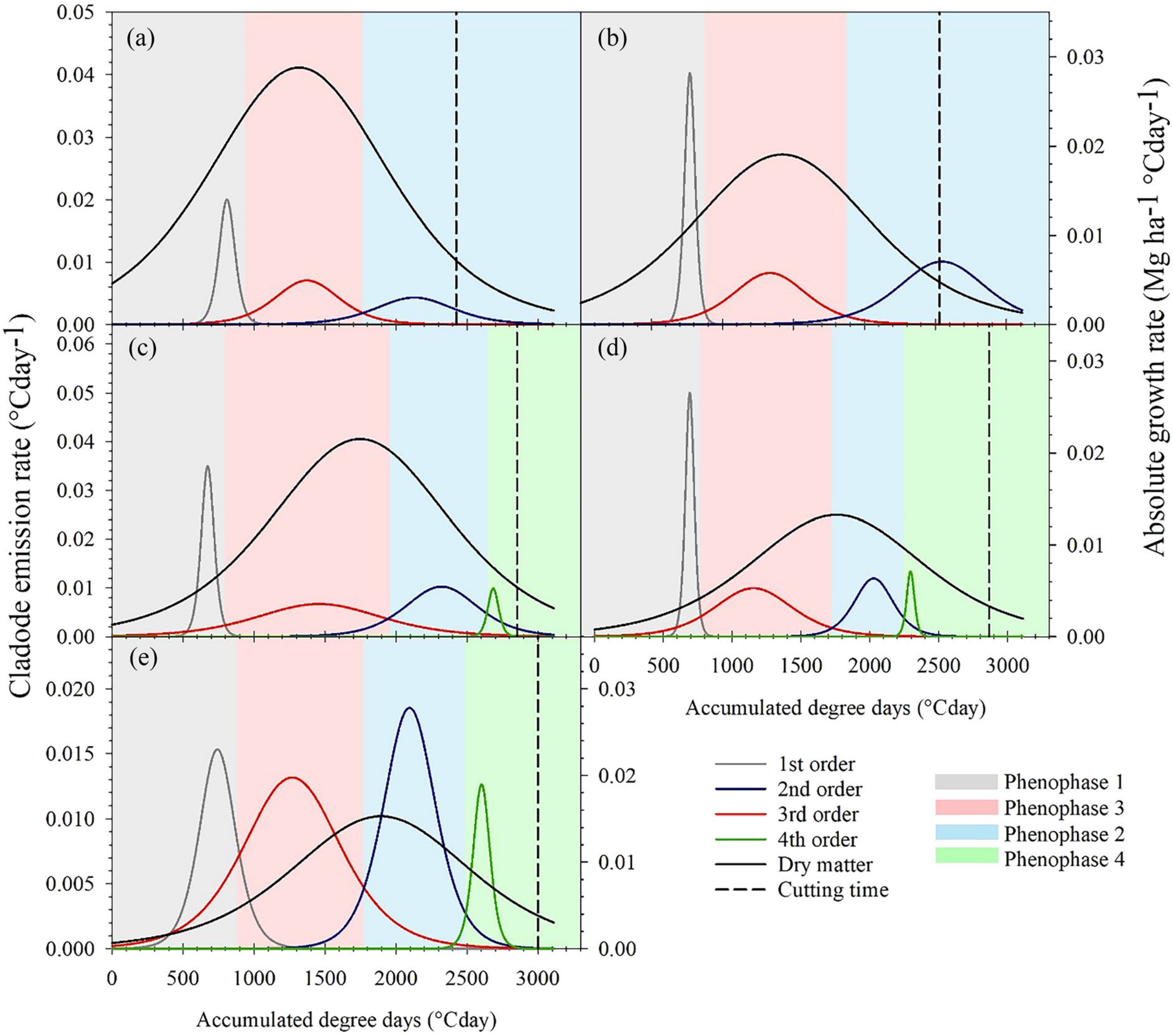

FIGURE 11 Plant phenophase and cutting time in forage cactus grown in east–west orientation and intercropped with sorghum 467 under different planting densities. (A) 100,000 plants ha^{-1}; (B) 50,000 plants ha^{-1}; (C) 33,333 plants ha^{-1}; (D) 25,000 plants ha^{-1}; (E) 20,000 plants ha^{-1}.

different planting densities, which was affected by changes in the spacing between rows, where the duration and number of phases are dependent on the planting density. Three phenophases occurred at each density under study, with the addition of Phenophase 4 at the lowest density (Figure 13D; 28,570 plants ha^{-1}).

The duration of Phenophase 1 was similar between treatments, with a mean duration of 1,043 °Cday (260 days). For the second phase, the duration was shorter at the lowest planting density (Figure 13D) than at the other planting densities, with a mean of 560 °Cday (140 days), despite showing the highest rate of cladode emission.

Dry matter accumulation varied as a function of the applied planting density (Figure 13). The maximum rate of accumulation was observed at a density of 50,000 plants ha^{-1} (Figure 9A), with a value of 0.032 Mg ha^{-1} °Cday^{-1} occurring at 1600 °Cday (400 days). In turn, the cutting time was brought forward at the highest density (Figure 9A; 50,000 plants ha^{-1}) compared to the other densities, with harvesting occurring at 2382 °Cday (595 days), whereas at the lowest density (Figure 9D; 28,570 plants ha^{-1}), the cutting time was delayed, occurring at 2555 °Cday (638 days).

4 | DISCUSSION

4.1 | Morphophysiological indices of forage cactus and sorghum

The variation in morphophysiological characteristics between clones is associated with the adaptation of each genotype, reflected in the morphology (Nunes et al., 2020), where the characteristics are dependent on the species (Amani et al., 2019). In addition, growth

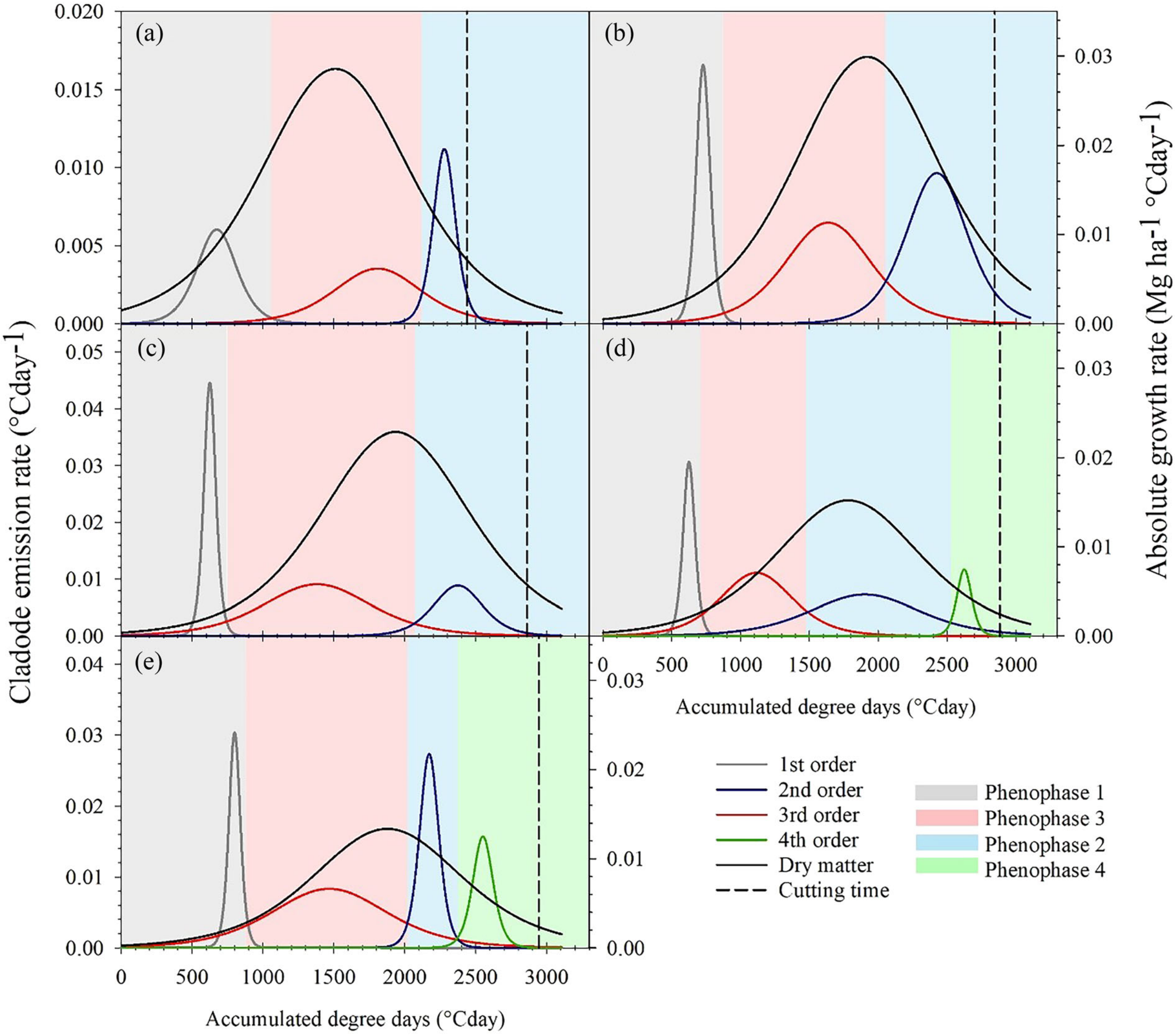

FIGURE 12 Plant phenophase and cutting time in forage cactus grown in north–south orientation and intercropped with sorghum 467 under different planting densities. (A) 100,000 plants ha^{-1}; (B) 50,000 plants ha^{-1}; (C) 33,333 plants ha^{-1}; (D) 25,000 plants ha^{-1}; (E) 20,000 plants ha^{-1}.

dynamics in forage cactus are dependent on factors such as the age of the crop, water regime and weather variables, especially air temperature, when the water supply is not limiting (Scalisi et al., 2016).

The crop growth rate (AGR) represents the variation or increase in the growth of the crop between samples over time (Zuffo et al., 2016). In general, the AGR is the ability to accumulate dry matter over space and time (i.e. per unit area and time) (Nunes et al., 2020). The highest values obtained in the systems with the OEM clone are associated with the characteristics of the species, which present a large CA, favouring an increase in resource use efficiency, especially light interception, and promoting an increase in dry matter accumulation. Silva et al. (2015), studying forage cactus clones, reported that compared with the IPA and MIU clones, the OEM differed in terms of the CA. In addition, IPA and MIU show high mortality, unlike the OEM clone (Jardim et al., 2021), making it difficult to accumulate dry matter per unit area since high-mortality crops have a reduced stand. For the sorghum cultivars, the highest rates were observed for the P.288 cultivar (113.36 Mg ha^{-1}), which is due to the greater capacity of this crop to accumulate dry matter compared to that of the SF11 (99.96 Mg ha^{-1}) and 467 cultivars (89.97 Mg ha^{-1}). However, the rate decreased with each cycle, regardless of the treatment or experimental area under evaluation, reflecting the reduction in productive vigour of the crops with each successive cut made when harvesting.

In turn, the highest values in the cactus, in both the east–west and north–south orientations, are associated with greater dry matter accumulation per unit area. Cavalcante et al. (2014) and Silva et al. (2014b) studied the forage cactus under different planting densities and showed

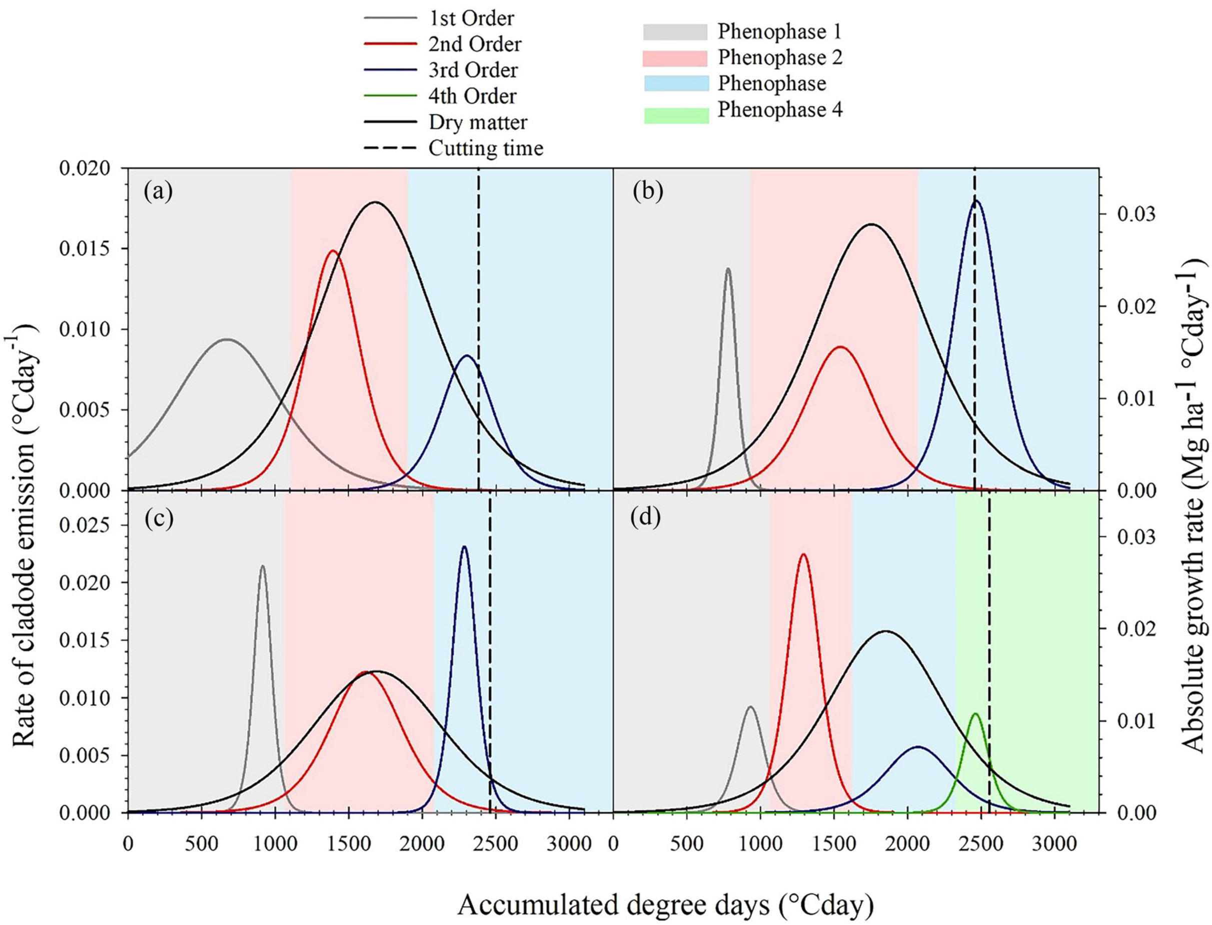

FIGURE 13 Plant phenophase and cutting time in forage cactus intercropped with sorghum 467 under different planting densities resulting from changing the spacing between rows. (A) 50,000 plants ha^{-1}; (B) 40,000 plants ha^{-1}; (C) 33,333 plants ha^{-1}; (D) 28,571 plants ha^{-1}.

that as the density increased, the morphometry of the genotypes increased, with the increase in density promoting a reduction in cladode emission and in CL and CW, just as an increase in crop productivity promoted greater nutrient and dry matter accumulation. In turn, when the cactus is grown in an east–west direction, productivity increases, a reflection of greater light capture favouring the photosynthetic process (Peixoto et al., 2018).

The lack of any difference in AGR in sorghum when grown in either an east–west or north–south direction is due to the fact that only the cactus was subjected to different planting densities, unlike the result of sorghum undergoing a change in density (Figure 9), where the density influenced the capacity for dry matter accumulation. A change in the spacing between crop rows influences the AGR of the crop (Silva et al., 2010). The difference in AGR under different planting densities is associated with competition, especially light capture, since the amount of incident solar radiation determines changes in the AGR (Terra et al., 2012).

The RGR indicates the increase in dry matter in relation to the amount of pre-existing dry matter for any given period (Queiroz et al., 2015). In the systems that included the P.288 cultivar, the lowest evaluated density resulted in the highest initial values for the RGR, which may be due to cell growth and development of the composition of new tissue, promoting an increase in LA (Terra et al., 2012). In turn, the reduction in RGR values as the crop grows is related to the increased need for photoassimilates for maintaining other already formed organs (i.e. leaves, stems, flowers and fruits) (Silva et al., 2010). Furthermore, the decrease in RGR values over time is associated with high crop shading and a reduced increase in the photosynthetically active area throughout the plant cycle (Silva et al., 2009).

In general, the RGR reflects plant growth, which is dependent on accumulated material, so that any reduction in RGR, in addition to being associated with the above factors, is due to the production of nonphotosynthetic organs (Teixeira et al., 2015). The authors also noted that the most productive cultivars showed faster growth and, generally, rapid development of the LAI.

The NAR is correlated with LA and dry matter production (Queiroz et al., 2015), reflecting the photosynthetic efficiency of organs (Zuffo et al., 2016). This index shows the efficiency of the photosynthetic organs for biomass production (Dantas et al., 2009). An increase in the NAR as the crop grows may be associated with an initial investment in LA, as well as the photosynthetic capacity of the species (Câmara et al., 2017). This index represents the balance between the product of photosynthesis and the material lost in respiration and, as such, decreases at the end of the cycle (Silva et al., 2009); in cases where there is an increase in values near the end of the cycle, this is associated with a delayed increase in LA.

In the case of forage cactus, the reduction in NAR is caused by the emission of new-order cladodes, which, during their young phase, have a lower photosynthetic capacity than more mature cladodes (Queiroz et al., 2015). The interaction between the crop and the environment impacts production in such a way that factors such as growth habit, angle of leaf/cladode insertion and disposition of the canopy influence the use of solar energy (Pinheiro et al., 2014). Ramos et al. (2017), studying forage cactus under different spacings, reported that an increase in planting density resulted in an increase in the CA and in the CAI, favouring a larger photosynthetically active area, where an increase in density promoted changes in the thickness, number and area indices of the cladodes (Donato et al., 2014). However, an increase in shading caused by the larger companion crop reduces the photosynthetic capacity (Peixoto et al., 2018).

The SCA expresses the relationship between dry matter production and the CAI, which quantifies the dry matter distribution in photosynthetic organs (Queiroz et al., 2015). This index tends to decrease over time, even after the CA stabilizes, with an increase in conducting tissue and, consequently, the accumulation of dry matter (Nunes et al., 2020). For configurations that include the OEM clone, the higher values compared to the configurations with IPA and MIU are related to the larger CA of this clone (Silva et al., 2015). In turn, high planting densities cause the crop to show a reduction in the number and development of cladodes, reflecting overlap (Cavalcante et al., 2014).

The SLA represents the ratio between the LA of a crop and the LDM, where the LA is a morphophysiological component and the dry matter is anatomical (i.e. size and number of cells) (Dantas et al., 2009). Increases in this index are associated with the plant investing more in photoassimilates, reflecting an increase in LA and a reduction in leaf matter density (Gobbi et al., 2011). In general, increases in the SLA occur as a result of the compensation mechanism, which allows the plant to increase its LA with a reduction in leaf thickness, resulting in greater absorption of the incident radiation (Schmidt et al., 2017). As such, the increases found during the initial phase of sorghum in the treatments applied in this study are associated with the crop mechanism for increasing the LA to increase the photosynthetic area, resulting in an escape response in relation to shading. In turn, a reduction in the SLA is an indication that there was an increase in leaf matter as a function of LA.

The LAR represents the photosynthetic LA, that is, the relationship between the LA responsible for light interception and CO_2 and the total dry matter of the plant, and demonstrates the investment of the crop in photosynthetic production (Pinto et al., 2017). The increasing tendency of LAR values during the initial phase shows that during this period, plants convert photosynthetic production into LA (Silva et al., 2009), favouring a larger area for light capture and increasing dry matter accumulation in the crop. The reduction in the LAR with crop growth is due to a smaller active LA, which is a result of self-shading due to interference from the upper leaves on the light incident on the lower leaves (Silva et al., 2005). The higher values at the highest planting density are associated with the crop investing in LA, making it possible to increase light interception, which is reflected in an increase in crop dry matter.

In turn, the LMR expresses the relationship between LDM and the total dry matter of the plant (Zuffo et al., 2016). Its continuous reduction throughout each sorghum cycle is due to the greater conversion of photoassimilates into leaf products during the initial period of each cycle, promoting an increase in the efficiency of light interception, as well as the subsequent production of drain structures (Silva et al., 2009). Higher values of LAR and LMR at higher densities are associated with greater production of LDM from photosynthesis (Terra et al., 2012). This is due to greater investment in leaf production than in other plant organs, which is a mechanism to avoid shading.

4.2 | Phenophase and cutting time of forage cactus

Phenological delimitation is an important aid in decision-making and planning in a production system. For forage cactus, phenological delimitation can be determined by the rate of cladode emission in order of appearance (first order, second order, etc.), helping producers to properly manage the crop (Amorim et al., 2017). The duration and number of phenological phases are dependent on the species and cropping conditions, and it is known that the morphological characteristics of the forage cactus are directly influenced by the genotype and management employed (Silva et al., 2009). The greater number of phenophases found in the configurations that comprised the MIU clone is associated with the characteristics of the clone, where the cladode dimensions (i.e. height and width) are smaller than those of the other clones (Pereira et al., 2015) and therefore require less energy for the emission of new cladodes, which is reflected in the larger number of higher-order cladodes. Silva et al. (2015) reported that in the MIU clone, cladode emission was greater, mainly due to the presence of higher-order cladodes (i.e. third-order and fourth-order); however, the CAI was lower, precisely because of the reduced size of the cladodes. This characteristic of cladode emission is intrinsic to the MIU clone (Araújo Júnior et al., 2021a). In addition, the smaller number of phenophases and longer duration of Phenophase 2 in the OEM and IPA clones are associated with the structural characteristics of the genotypes. Nunes et al. (2020), studying these clones, reported that the distribution of cladodes on plants is greater for first- and second-order cladodes than for MIU, which has a greater distribution of higher-order cladodes (>second order).

In turn, the choice of planting density promotes changes in the morphological and physiological characteristics of crops (Rosa et al., 2020). The greatest number of phenophases was found at the lowest density due to less intraspecific competition for available resources (i.e. water, light and nutrients) compared to denser plants. Furthermore, the emission of higher-order cladodes was greater in the less dense crops than in those at a higher density (data not shown). Silva et al. (2014a), studying genotypes of the genus *Opuntia*, reported that as the planting density increased, the number of cladodes decreased.

The changes in the duration and number of phenophases resulting from modifying the production system influenced the rate of dry matter accumulation and consequently the cutting time of the forage cactus. Silva et al. (2020) reported that the CAI and the number of cladodes influence production characteristics. Jardim et al. (2020) reported that the length, width, perimeter and area of the cladodes, as well as the genus of the plant species, are determining factors in biomass accumulation in the forage cactus. As such, the maximum rate of dry matter accumulation in the OEM clone compared to the IPA and MIU clones is related to the high values for CA, which favour water accumulation and a larger photosynthetic area in addition to a greater capacity for matter accumulation and high water use efficiency (Araújo Júnior et al., 2021a; Silva et al., 2014b). There was a delay in harvesting the forage cactus when the production system included the P.288 cultivar, which was ready for cutting at 1803 °C day (450 days), followed by the systems containing the 467 cultivar (1,637 °C day—409 days) and the SF11 cultivar (1,562 °C day—390 days). On the other hand, the monocropped clones showed a reduction in harvest time and were ready for cutting at 1387 °C (346 days). These results are associated with the interspecific competition between the intercropped plants and the single crops, which promotes changes in the storage of photoassimilates and consequently a reduction in dry matter accumulation (Makino et al., 2019), requiring the crop to remain longer in the field.

The results also showed that an increase in planting density promoted an increase in crop productivity, enabling greater dry matter accumulation and anticipating the harvest. That said, the cactus cultivated at a density of 100,000 plants ha^{-1} showed an earlier harvest regardless of orientation, with cutting carried out at 2431 °Cday (~607 days) on average, different from the crop at the lowest density (20,000 plants ha^{-1}), which presented a delay in harvest and was ready for cutting at 2975 °Cday (~743 days), that is, with the increase in planting density, the cactus required 544 °Cday (~136 days) less than at the lowest density. This same behaviour was observed when the crop was grown at different densities by changing the spacing between rows, where at the highest planting density (50,000 plants ha^{-1}), the cut could be anticipated, occurring at 2382 °C day (~595 days); on the other hand, at the lowest planting density (28,571 plants ha^{-1}), the crop presented a delay in harvest and was ready for cutting at 2555 °C day (~638 days). This means that at the lowest density, the crop needs more time in the field to reach the ideal harvest time. These results may be due to the increase in photosynthetic efficiency resulting from increases in the CAI (Souza et al., 2017).

With the increase in dry matter accumulation due to the abovementioned characteristics, there is a change in cutting time, where the crop tends to have an earlier harvest, unlike those with lower rates of accumulation. The delay in harvesting when intercropped with the P.288 cultivar, for example, is associated with greater competition between the companion crops compared to the other configurations since this cultivar has a larger LA relative to the other cultivars (data not shown), resulting in a larger photosynthetic area, in addition to promoting greater shading of the forage cactus. Plants require sunlight, and when shaded, light interception is reduced, which has a direct effect on the characteristics that determine crop productivity (Paciullo et al., 2008). Intercropping systems can modify the microclimate of planted areas, especially in relation to the luminosity received by crops (Wang et al., 2021). Araújo et al. (2015), studying an intercropping system, reported that the system promoted a reduction in the incidence of radiation. Light interception is crucial for crop productivity: In an intercropping system, there are both large and small species, with a given amount of light passing through the canopy of the larger crop and affecting productivity in the smaller plants (Gong et al., 2020). When the cactus is shaded, light capture is reduced, and as a result, the rate of dry matter accumulation is directly reflected during the cutting time. On the other hand, since the monocropped configurations remain in full sun, harvest is anticipated, favouring light interception and converting it into dry matter.

5 | CONCLUSIONS

The morphophysiological characteristics vary depending on the cropping system used, with higher rates in configurations that include the OEM cactus clone, as well as at the highest densities under study (50,000 and 100,000 plants ha^{-1}). In turn, the values for sorghum vary for the cropping configuration and planting density, with a reduction in rates as the cycles continue.

In the forage cactus, cropping configuration and planting density promote variations in the duration and number of phenophases and in the cutting time. The MIU-SNG configuration had a greater number of phases. In contrast, configurations that included the OEM clone presented fewer phases; however, they did show greater dry matter accumulation, as seen at the highest planting densities under study (50,000 and 100,000 plants ha $^{-1}$), resulting in an increase in cutting time.

Using the OEM clone with sorghum forage is therefore recommended in intercropping systems, together with the highest densities used in this study (50,000 and 100,000 plants ha^{-1}), with the aim of increasing dry matter accumulation per unit area and anticipating harvest. It is suggested that research be developed with a view to intercropping cactus and other forage plants (e.g. corn, elephant grass, pigeon pea and *Gliricidia*) under different production systems (e.g. planting density, use of mulch and cultivation orientation) and irrigation with salt water to improve the understanding of crop growth and development.

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DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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