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Management Strategies and Agricultural Calendars for Forage Production in Semi-Arid Brazil Using AquaCrop

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ABSTRACT

Forage production in semi-arid regions of Brazil is limited by water deficit. This study aimed to identify the most adapted and efficient production systems and define their agricultural calendars for the semi-arid region of Brazil. Twenty-nine production arrangements that included different cropping conditions, plant density, plant cycles, water replenishment, use of soil cover and production arrangements based on the main crop (forage cactus) were simulated for 14 locations. On the basis of the agricultural calendar, planning from the beginning of December to January is ideal for rainfed systems. Compared with their monoculture systems, the intercropping system of forage cactus and irrigated sorghum increased the forage supply by 44% and 89%, respectively. The use of irrigation increased the forage cactus biomass by 150%, with an emphasis on the clone Orelha de Elefante Mexicana, which presented an average water productivity of 39 $g\,m^{-2}$. The increase in the planting density of the forage cactus increased productivity by up to 140% under the control. The use of irrigated forage cactus and sorghum intercropping should be recommended, in addition to practices such as higher planting densities and the use of mulch to optimise yield.

Résumé

La production de fourrage dans les régions semi-arides du Brésil est limitée en raison du déficit hydrique. Cette étude visait à identifier les systèmes de production les plus adaptés et efficaces et à définir leurs calendriers agricoles pour la région semi-aride du Brésil. Vingt-neuf modes de production, qui comprenaient différentes conditions de culture, densité des plantes, cycles de culture, réapprovisionnement en eau, utilisation de la couverture du sol et modes de production basées sur la culture principale

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(cactus fourrage), ont été simulées pour 14 sites. Sur la base du calendrier agricole, la planification de début décembre à janvier est idéale pour les systèmes pluviaux. Par rapport à leurs systèmes de monoculture, les cultures mixtes irriguées de cactus fourrager et de sorgho ont augmenté l'approvisionnement en fourrage de 44% et 89%, respectivement. L'utilisation de l'irrigation a augmenté la biomasse de cactus fourrager de 150%, avec un accent mettant sur le clone Orelha de Elefante Mexicana, qui présentait une productivité moyenne de l'eau de 39 g m^{-2}. L'augmentation de la densité de plantation du cactus fourrager a augmenté la productivité jusqu'à 140% dans le cadre du contrôle. L'utilisation de cultures mixtes irriguées de cactus fourrage et de sorgho devrait être recommandée, en plus de pratiques telles que les densités de semis plus élevées et l'utilisation de paillis pour optimiser le rendement.

1 | Introduction

Low fodder production is characteristic of semi-arid regions because of factors such as high evapotranspiration demands, irregular rainfall and inefficient management interventions, thus unbalancing the supply of food for herds over the years (Bell et al. 2018; Moraes et al. 2019; Veloso et al. 2020; Pinheiro et al. 2021). The semi-arid region of Brazil (SAB) is 982,566 km^2, representing 18% of the country (Pinheiro et al. 2024), with average annual rainfall ranging from 400 to 800 mm (Alvares et al. 2013; Silva et al. 2021).

Based on rainfall, the SAB can be divided into three primary geographical zones: (a) the northern zone, which covers most of the semi-arid region with rainfall concentrated between December and May and is influenced by the Intertropical Convergence Zone (ITCZ); (b) the south/southeast zone, where the greatest rainfall occurs from November to February and is associated with cold fronts from the south; and (c) the eastern zone, where the peak rainfall period extends from April to August and is driven mainly by thermal differences between the Atlantic Ocean and adjacent lands, all of which influence management interventions for agricultural crops (Cunha et al. 2015).

As a result of the characteristics of each geographical area, efforts are being made to minimise the restrictions on forage production, known as 'yield gaps', to understand and quantify the disparity between potential and actual crop yields (Sentelhas et al. 2015; Beza et al. 2017; Dias and Sentelhas 2018; Monteiro et al. 2020; Pinheiro et al. 2024).

An alternative to ensure greater productive return is the implementation of resilient agricultural practices, such as the adoption of forage crops adapted to the climate. Studies highlight the potential of forage cactus (*Nopalea* spp. and *Opuntia* spp.), which presents crassulacean acid metabolism (CAM), known for its high efficiency in the use of water and productivity, even under conditions of prolonged drought (Queiroz et al. 2015; Moraes et al. 2019; Pessoa et al. 2020). In addition, sorghum and millet are highly important because of their nutritional value and high productivity, which are attributed to their C4 metabolism (Alves et al. 2022; Jardim et al. 2020).

In addition to adapted species, increased crop density and intercropping can contribute to greater crop sustainability, ensuring greater productivity per area and nutritional balance for livestock (Queiroz et al. 2015; Diniz et al. 2017; Araújo Júnior, Silva, Souza, Araújo, et al. 2021; Jardim et al. 2021; Pinheiro et al. 2024). In addition, productivity levels can be increased when crops are managed under irrigation, using crop evapotranspiration (ETc) as a reference to avoid waste and provide only what is necessary for good crop development (Amorim et al. 2017; Araújo Júnior, Silva, Souza, Araújo, et al. 2021; Sá Souza et al. 2022; Lima, Silva, Pereira, et al. 2018; Pereira et al. 2020).

Although these practices provide greater security for semi-arid regions, determining the ideal planting time, with a view to greater canopy development and reducing thermal and water stress during the critical growth stages of the crop, is essential (Santos et al. 2017; Zhang et al. 2019). However, there is limited detailed information on the agricultural calendar for forage crops such as forage cactus, sorghum and millet in the semi-arid region of Brazil. The available data are mainly restricted to the Agricultural Zoning for Climate Risk (AZCR). Although AZCR is a valuable risk management tool, there is still a need to improve interspecific information for these crops and their respective cultivation systems.

To meet these challenges, the AquaCrop simulation model, developed by the Food and Agriculture Organisation (FAO) of the United Nations, serves as a valuable tool for determining the ideal fodder production arrangements in different locations. It also makes it possible to estimate production scenarios based on various agricultural practices. AquaCrop was designed to simulate the effects of environmental conditions and management strategies through three modules: soil water balance, crop growth simulation and atmospheric composition (Zhu et al. 2021). The model produces reliable results with relatively minimal data input (Heng et al. 2009; Hsiao et al. 2009; Raes et al. 2009).

AquaCrop has been successfully applied to several crops, including potato (Linker et al. 2016; Razzaghi et al. 2017), sugarcane (Bahmani and Eghbalian 2018; Farooq and Gheewala 2020), sunflower (Saab et al. 2014), common bean (Magalhães et al. 2019), soybean (Adeboye et al. 2021; Giménez et al. 2017), millet (Bello and Walker 2016; Guo et al. 2018), maize (Van Gaelen et al. 2015; Zhu et al. 2021) and sorghum (Araya et al. 2016; Hadebe et al. 2017). However, few studies have applied this model to fodder cactus or investigated the productive responses of sorghum and millet under different cropping systems in the semi-arid region of Brazil, particularly under rainfed and irrigated conditions.

Therefore, our hypothesis is that AquaCrop can be used to carry out simulations of the best planting times for forage cactus and sorghum crop arrangements in semi-arid environments. This study aims to (i) use the AquaCrop model to identify the most

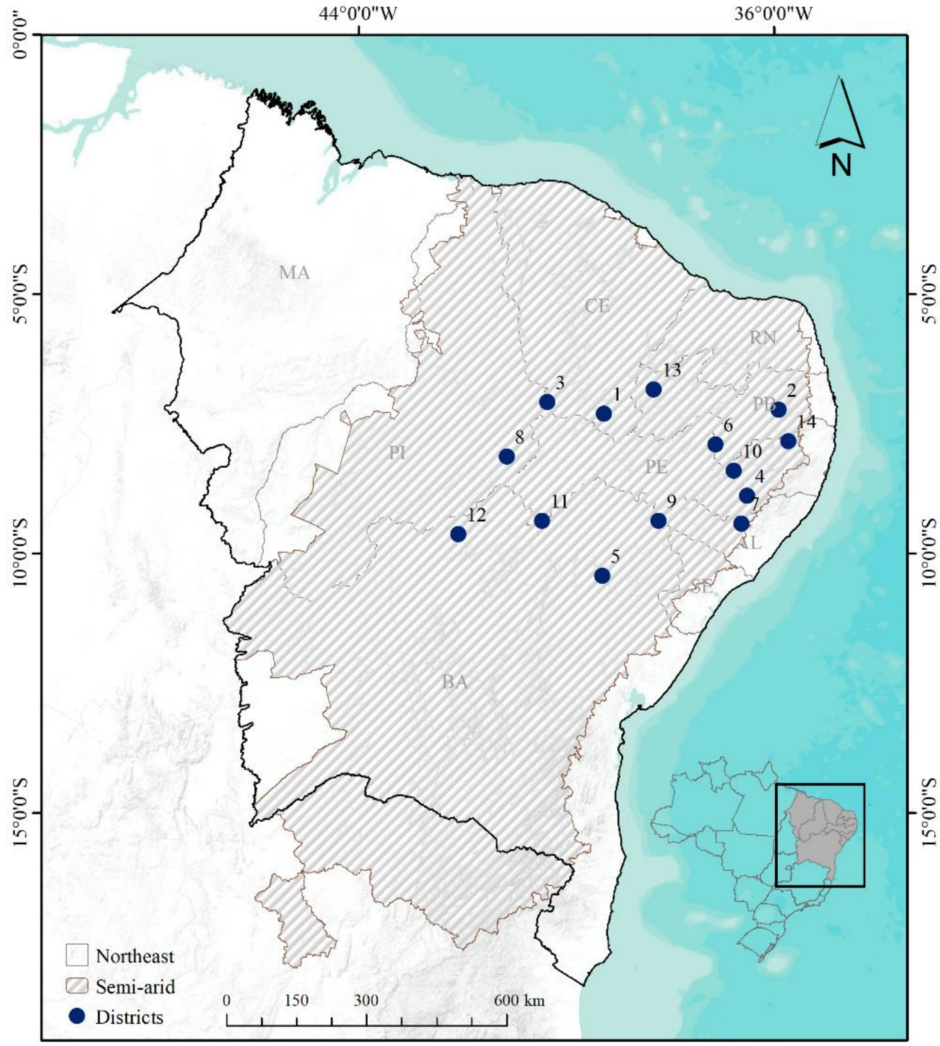

FIGURE 1 | Locations of the districts used for application of the AquaCrop model.

adapted and efficient production systems under the environmental conditions of the SAB and (ii) optimise the agricultural calendar for fodder crops.

2 | Materials and Methods

2.1 | Description of the Study Area

The AquaCrop model was used in 14 locations across Brazil's semi-arid region (Figure 1), which has distinct climates, rainfall, temperatures and reference evapotranspiration (ET_0) (Figure 2). The sites are in six states: Alagoas, Bahia, Ceará, Paraíba, Pernambuco and Piauí. Rainfall is concentrated in the first half of the year (72.6%) (Figure 2). The annual rainfall ranges from 500 (Petrolina) to over 900 mm (Barbalha, Garanhuns and São Gonçalo). The temperature and ET_0 show similar patterns. Garanhuns has the lowest average temperature (21.9°C), whereas Paulistana has the highest (27.5°C). Remanso has the smallest temperature variation (1.0°C), and Petrolina has the largest (4.3°C). These factors directly influence ET_0, which is highest in Paulistana and lowest in Garanhuns.

2.2 | Description of the Cropping Conditions and Agricultural Arrangements Used in the Simulations

From the study conducted by Pinheiro et al. (2024), who carried out parameterisation of the AquaCrop model for different forage crops and agricultural systems, we chose the arrangements showing the most potential for the semi-arid region of Brazil. As such, six types of crops under 29 agricultural arrangements were simulated for each district and included different levels of densification, different vegetative cycles and water replacement based on the main crop (forage cactus). It should be noted that these simulated agricultural scenarios are the result of appropriate cropping conditions and agricultural management, as highlighted by Alves et al. (2022), which imply well-fertilised fields,

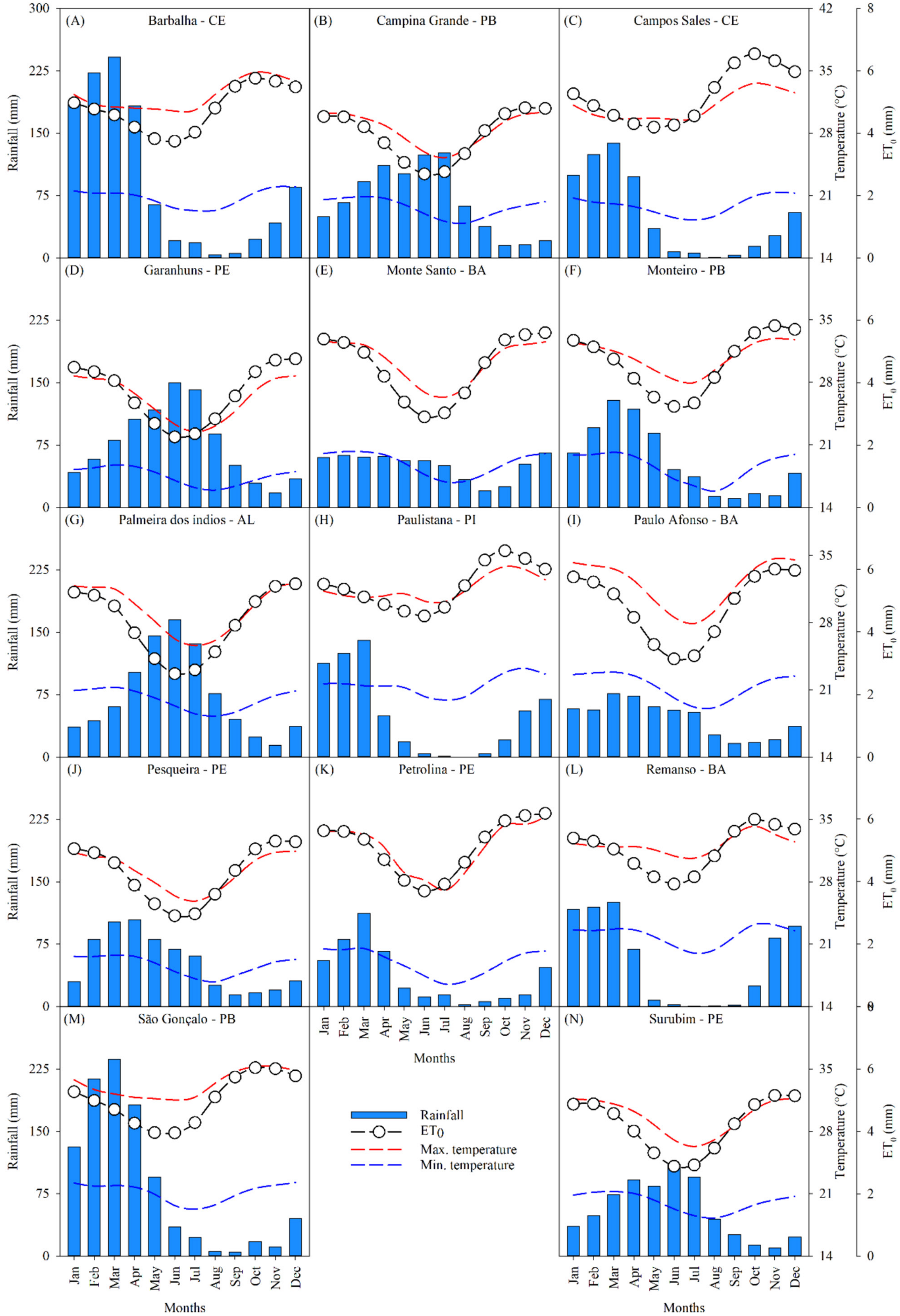

FIGURE 2 | Distribution of the monthly historical average for the climate variables of temperature (°C), rainfall (mm) and reference evapotranspiration—ET_0 (mm).

under proper spacing, with pest and weed control. Table 1 highlights the conditions and agricultural arrangements applied in the simulations of biomass production for the different locations in the semi-arid region of Brazil.

The following systems were applied: 'rainfed and single' (IPA-RS, MIU-RS, OEM-RS, 267-RS, P288-RS, SF11-RS); 'irrigated and single' (IPA-IS, MIU-IS, OEM-IS, 467-IS, P288-IS, SF11-IS); 'intercropping and rainfed' (IPA-SF11-R, MIU-P288-R, OEM-SF11-R); and 'intercropping and irrigated' (IPA-SF11-I, MIU-288-I, OEM-SF11-I). For the systems under irrigation management at different depths and frequencies, an irrigation depth of 80% of the ETc (IPA-80%, MIU-80%, OEM-80%) was applied, in addition to the systems with the IPA clone at an irrigation frequency of 7 days (IPA-07D), Miúda at 28 days (MIU-28D) and OEM at 14 days (OEM-14D). Furthermore, owing to the influence of the mulch, the OEM clone was defined for the conditions of 'rainfed with cover' (OEM-RWC) and 'irrigated with cover' (OEM-IWC); in addition, the systems with the OEM clone under complementary irrigation (OEM-CI) and for the conditions of 'rainfed and dense' (OEM-RDN.) and 'irrigated and dense' (OEM-IDN).

2.3 | Description of the AquaCrop Model, Data Entry and Application to the 14 Locations

AquaCrop is a model of crop growth and development proposed by the FAO (Hsiao et al. 2009; Raes et al. 2009; Steduto et al. 2009) and was developed to analyse the influence of

TABLE 1 | Description of the production units of forage cactus and sorghum, including intercropping systems, different clones, different water regimes, irrigation frequencies and planting density.

Cropping condition	Plant density (plants ha^{-1})	Plant cycle	Water replacement	Use of ground cover	Productive arrangements
Forage cactus–sorghum intercropping under complementary irrigation	Cactus—50,000 Sorghum—200,000	Forage cactus Sorghum	0% ETc 80% ETc	No cover	IPA-RS MIU-RS OEM-RS 267-RS P288-RS SF11-RS IPA-IS MIU-IS OEM-IS 467-IS P288-IS SF11-IS IPA-SF11-R MIU-288-R OEM-SF11-R IPA-SF11-I MIU-288-I OEM-SF11-I
Forage cactus clones under different water regimes	Cactus—50,000	Forage cactus	80% ETc	No cover	IPA-80% MIU-80% OEM-80%
Forage cactus clones subjected to different irrigation frequencies	Cactus–50,000	Forage cactus	Fixed irrigation depth of 14 mm Frequencies IPA—7 days OEM—14 days MIU—28 days	No cover	IPA-07D OEM-14D MIU-28D
Forage cactus with and without mulch	Cactus—31,250	Forage cactus	0% ETc 120% ETc	Mulch (15 Mg ha^{-1})	OEM-RWC OEM-IWC
Forage cactus under complementary irrigation	Cactus—41,667	Forage cactus	100% ETc	No cover	OEM-CI
Different densities of the forage cactus under rainfed and irrigated conditions	Cactus—200,000	Forage cactus	0% ETc 100% ETc	No cover	OEM-RDN. OEM-IDN

climate conditions and agricultural management on the productive response of crops. The AquaCrop model (version 6.1–No. 02052018) consists of three modules: composition of the atmosphere, water balance and crop growth (Zhu et al. 2021). The model shows excellent performance in separating evapotranspiration (ET) into soil evaporation (E) and crop transpiration (Tr), expanding our knowledge of the effect that water has on the productive consumption of plants (Steduto et al. 2009). As a result, the final yield is expressed by the biomass (*B*) and harvest index (*HI*), as shown in Equations (1) and (2), respectively.

$$Y = B \times HI \tag{1}$$

$$B = WP \times \sum Tr \tag{2}$$

where Y is the final yield ($Mg\,ha^{-1}$), B is the biomass ($Mg\,ha^{-1}$), HI is the harvest index, WP is the water productivity parameter ($kg\,m^{-2}\,mm^{-1}$) and Tr is the transpiration rate (mm).

The necessary input data for the model was divided into five sets: (1) climate data; (2) irrigation data; (3) soil data; (4) crop and production system parameters; and (5) agricultural management data.

2.3.1 | Climate Data

The set of climate data comprises the daily variables of maximum temperature, minimum temperature, rainfall and reference evapotranspiration, the latter of which is estimated via the Penman–Monteith equation (Allen et al. 1998). The climate data were obtained from the National Institute of Meteorology (INMET). The dataset, with a duration of 57 years (1961–2018), was organised on a daily scale; mean values were established to create the daily average series. This routine ensured complete continuous series for simulating productivity and the agricultural calendar over an entire average year. Figure 2 shows the climate data for each district.

2.3.2 | Irrigation Data

The irrigation for each district was estimated based on the crop evapotranspiration (ETc).

2.3.3 | Soil Data

The file for the soil data was organised as per the national database of soil profiles (Cooper et al. 2005) and set up to include the necessary information required by the model, such as texture, average depth, field capacity (FC), wilting point (WP) and hydraulic conductivity for each district (Table 2).

2.3.4 | Calibration and Validation of the AquaCrop Model for Different Production Arrangements

The AquaCrop model was calibrated using field-collected data, as detailed in the previously published study by Pinheiro et al. (2024), which describes the model calibration and validation process for forage cactus, sorghum and millet production systems under semi-arid conditions. In this study, the model parameters were adjusted using data from six production units, with a focus on phenological, biometric and biomass characteristics throughout the crop cycle. Climate, irrigation, soil and management data were collected and used to calibrate the model parameters, such as the vegetation cover growth coefficient (*CGC*), the vegetation cover decline coefficient (*CDC*), the

TABLE 2 | Main characteristics of the soil profiles for the districts under analysis.

		Soil depth	WP	FC	Water condition
District	Texture	m	%		$mm\ h^{-1}$
Pesqueira	Sandy	1.20	4.40	10.00	116.59
Petrolina	Sandy clayey loam	1.50	14.30	25.90	16.24
Surubim	Sandy	1.50	4.40	9.80	118.19
Garanhuns	Clayey	1.90	8.20	25.60	28.56
Paulo Afonso	Sandy loam	0.55	9.20	17.60	46.23
Palmeira dos Índios	Sandy loam	1.50	6.90	12.50	54.78
Barbalha	Sandy clay	1.68	14.90	26.00	15.00
Remanso	Sandy loam	0.50	11.50	19.80	31.95
Campos Sales	Sandy loam	1.10	10.30	18.30	39.59
Paulistana	Sandy clayey loam	0.95	15.40	26.30	13.67
Monteiro	Clayey loam	0.85	20.90	33.60	4.64
Campina Grande	Sandy loam	0.40	10.40	20.60	34.18
Monte Santo	Sandy loam	0.80	12.10	21.30	27.35
São Gonçalo	Sandy loam	0.55	5.20	14.30	83.02

TABLE 3 | Initial parameters used in calibrating the AquaCrop model.

Symbol	Description
	Air temperature
T_b	Basal temperature (°C)
T_B	Maximum temperature (°C)
	Canopy development
—	Time between planting and emergence (days or °C day^{-1})
—	Number of plants per hectare
CC_o	Initial canopy cover with 90% plant emergence (%)
CGC	Canopy growth coefficient (soil cover ratio per day or °C day^{-1})
CC_x	Maximum canopy cover (%)
—	Time from planting to the start of senescence (days or °C day^{-1})
CDC	Canopy decline coefficient (Ground cover ratio per day or °C day^{-1})
—	Time between sowing and maturation (days or °C day^{-1})
	Root zone development
Z_{min}	Minimum effective root depth (m)
Z_{max}	Maximum effective root depth (m)
—	Root zone expansion factor
—	Time between sowing and maximum root depth
	Crop transpiration
Kcb_x	Crop coefficient with maximum canopy expansion
f_{Kc}	Coefficient of crop decline as a result of age, nitrogen deficiency, etc. (% day^{-1})
—	Effect of canopy cover on reducing soil evaporation at the end of the cycle
	Biomass production and yield
$WP*$	Normalised water productivity for ET_0 and CO_2 (g m^{-2})
	Harvest index
HI_0	Reference harvest index
	Water stress
$P_{exp,\ upper}$	Upper limit of soil water depletion for canopy expansion
$P_{exp,\ lower}$	Lower limit of soil water depletion for canopy expansion

(Continues)

TABLE 3 | (Continued)

Symbol	Description
—	Water stress coefficient factor for canopy expansion
P_{est}	Upper limit of soil water depletion for stomatal control
—	Water stress coefficient factor for stomatal control
P_{sen}	Upper limit of soil water depletion for canopy senescence
—	Water stress coefficient factor for canopy senescence
	Air temperature stress
—	Minimum degree-days necessary for total biomass production (°C day^{-1})

Source: Hadebe et al. (2017); Heng et al. (2009).

maximum effective root depth and water productivity, as shown in Table 3.

The calibration process was performed through iterative adjustments of the most sensitive parameters of the model, such as normalised water productivity (*WP*), upper and lower limits of soil water depletion for vegetation cover expansion (P_{exp_upper} and P_{exp_lower}) and the upper limit of soil water depletion for vegetation cover senescence (P_{sen}). These adjustments were made until the simulated values of vegetation cover and biomass approached the values observed in the field, which were based on statistical indices such as the root mean square error (RMSE) and the coefficient of determination (R^2).

The model was validated using data from six independent production units, with results that demonstrated good model accuracy, with R^2 values above 0.80 and performance classified as 'very good' (confidence index > 0.80). These results confirm the effectiveness of the AquaCrop model in simulating crop productivity under different production arrangements, as detailed in the study by Pinheiro et al. (2024).

2.4 | Construction of the Agricultural Calendar

The simulations took place in such a way as to identify the variations and impacts caused by the agricultural calendar on the different cropping systems under analysis, exposing the risks with an interval of 0%–100% for minimum and maximum productive performance, respectively. For the intercropping system of forage cactus and sorghum, it was established that the sorghum would be planted 4 months after the start of the forage cactus cycle since the initial growth of sorghum is faster than that of forage cactus. This interval, attributed to an analysis of the research carried out by Jardim et al. (2021), affords the forage cactus greater stability and allows the cultivation and growth of sorghum. The start of the cycle of each cropping system was therefore simulated for the 15th of each month (15/01, 15/02, 15/03, 15/04, 15/05, 15/06, 15/07, 15/08, 15/09, 15/10, 15/11 and 15/12) and for all locations.

3 | Results

3.1 | Agricultural Calendar for Cropping Systems of Forage Cactus and Sorghum

Figure 3 shows, by means of simulations carried out by the AquaCrop model, the agricultural calendar for the single cropping systems of forage cactus clones (IPA, MIU and IPA) and sorghum cultivars (467, SF11 and P288), in addition to the intercropping systems that included these crops (IPA-SF11, MIU-P288 and OEM-SF11). All these systems were analysed with and without irrigation for each district, and the most appropriate planting dates for each location were estimated on the basis of their productive potential at the end of the cycle.

In general, when cultivation was carried out under rainfed conditions, e.g., without the use of irrigation, greater risks were observed throughout the year, including a reduced period for the start of cultivation. As a result, the period of cultivation presents the lowest risk of losses when carried out at the start of the rainy season in each district. However, when cultivation is carried out under irrigation, the risk of production losses is reduced, and the start of cultivation is extended, regardless of whether the crops are single or intercropped (Figure 3). The cultivation of forage under irrigated conditions resulted in increased production in all the systems for each district. On average, considering the forage cactus and sorghum, there was an increase in biomass production of approximately 137% and 157% for the single and intercropping systems, respectively. It is worth highlighting the district of Paulo Afonso; the highest proportional increases, 332% and 439%, occurred due to irrigation in the single and intercropping systems, respectively. The Orelha de Elefante Mexicana (OEM) clone of the forage cactus grown under irrigation offers greater productive return than the other clones do, in addition to allowing cultivation at almost any time of the year, with no significant risk to production.

Due to the lower annual temperature (21.9°C), the district of Garanhuns allowed more time to begin planting forage crops. However, when the cactus is grown as a single crop, the ideal period for planting is between March and June, with a risk of losses of approximately 20% (Figure 3), where as sorghum, which has a reduced cycle (~100 days), can be planted between February and June, with a less than 10% risk of loss. When the forage cactus clones were intercropped with the sorghum cultivars, planting between November and April presented

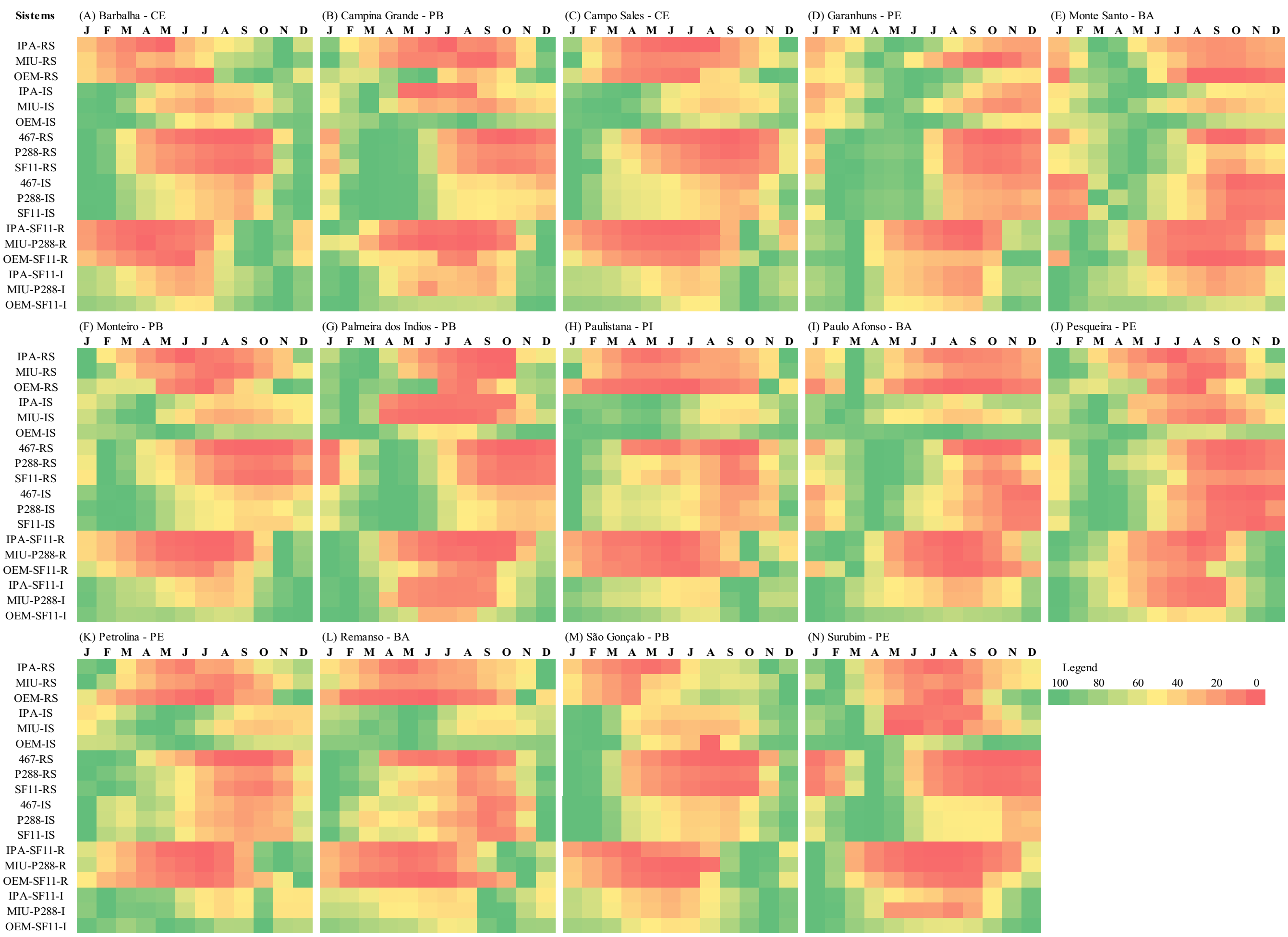

FIGURE 3 | Simulation of the agricultural calendar for clones of forage cactus (IPA, MIU, OEM) and sorghum (467, P288, SF11) grown as single crops (RS) and as intercrops under simulated rainfed (R) and irrigated (I) conditions.

the lowest risk (< 20%), provided that an interval of 4 months was allowed between planting the cactus and planting the sorghum. Moreover, productivity, the sum of the biomass in the intercropping system, increased to approximately 71% and 64% greater than that in the single crops under rainfed and irrigated conditions, respectively.

In the district of Petrolina, it is recommended that the forage cactus be planted and grown under rainfed conditions between December and January before the start of the rainy season. However, the use of irrigation management allows a longer period for the start of cultivation (February to July), with a less than 10% risk. In Petrolina, sorghum should preferably be planted in January, with less than 10% risk; this may be extended until April, with up to a 30% risk of loss, which is characteristic of cropping systems under rainfed and irrigated conditions.

3.2 | Effects of Agricultural Practices on Biomass Production in Forage Systems

The effects of adopting agricultural practices such as mulching, different irrigation frequencies and densification can be seen from the information shown in Figure 4. In general, when the forage cactus is planted between December and June, under irrigation of 80% of the ETc, there is a trend towards an increase in production and a reduction in losses. Under such conditions, the IPA clone has the shortest planting period (January to April) and the OEM the longest (December to June), considering a less than 20% risk of production loss. Figure 4 shows that, on average, for clones irrigated at 80% of the ETc, the OEM clone had the highest biomass production at each location, 3.8 and 3.0 times greater than those of the IPA and MIU clones, respectively.

The OEM clone was also responsible for greater production than the IPA and MIU clones at all locations when subjected to different irrigation frequencies. On average, the OEM clone with an irrigation interval of 14 days resulted in an increase of 137% in relation to the IPA clone with an irrigation frequency of 7 days and 75% compared with the MIU clone, which was irrigated every 28 days. There was a reduction in biomass production in the OEM clone grown with ground cover in a system with no irrigation; however, when the OEM system with ground cover was grown under irrigation, there was an increase of approximately 237% in biomass production compared with the system grown under rainfed conditions. This behaviour differed only for the district of Garanhuns, where production in the systems with and without irrigation showed similar values, with an increase of only 6% for the irrigated system (Figure 4). In almost all locations, irrigation combined with mulching reduced the risk of losses and extended the ideal planting period for the forage cactus. Among the systems under evaluation, densification of the OEM clone under irrigated conditions resulted in an increase of approximately 140% of that observed under the same conditions but without the use of irrigation. Such values for maximum biomass are possible, albeit subject to proper management, and the start of the cycle is based on the local agricultural calendar. From this, it can be seen that the OEM clone in a dense irrigated system afforded an increase in productivity and reduced the risk of losses in all locations where the start of the cycle was between December and January.

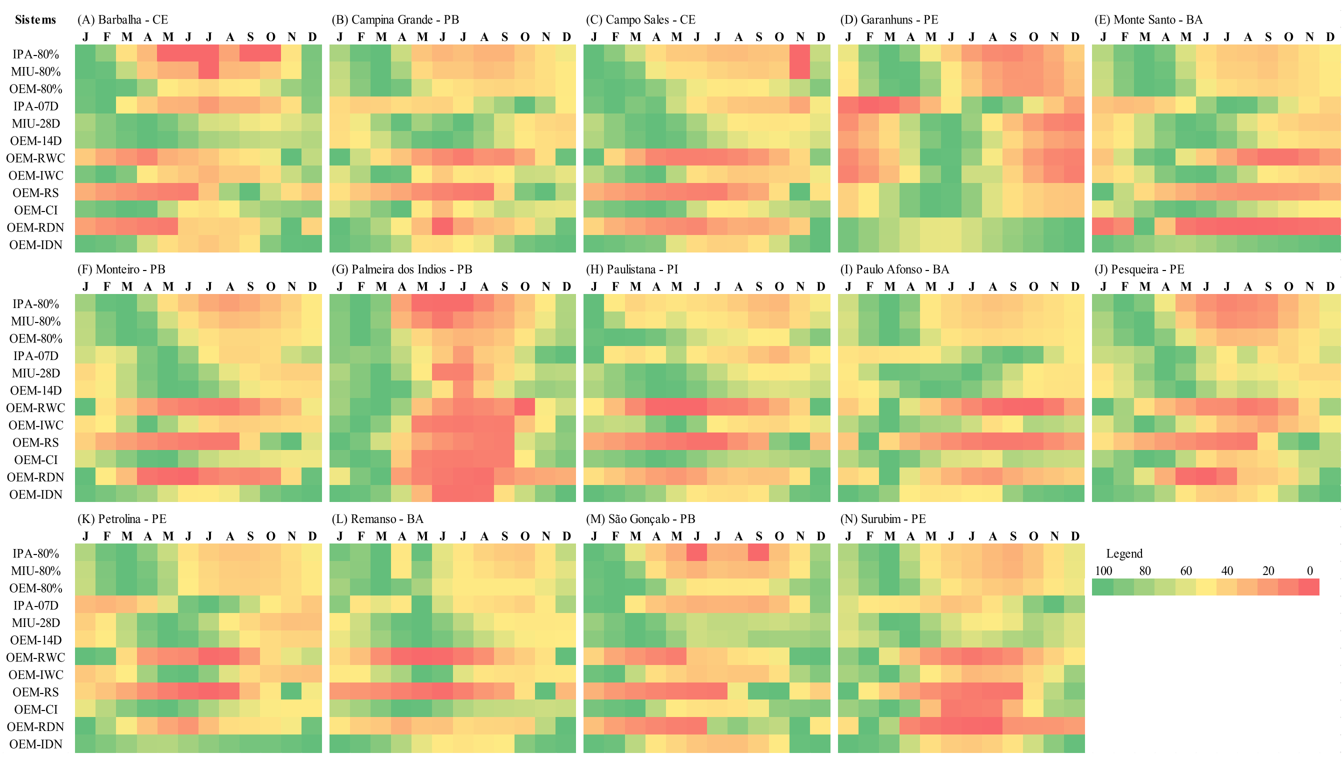

FIGURE 4 | Simulation of the productive response of the AquaCrop model for the IPA, MIU and OEM forage cactus clones under irrigation at 80% of the ETc (IPA-80%, MIU-80% and OEM-80%), IPA under an irrigation frequency of 7 days (IPA-07D) and MIU under different irrigation frequencies under simulated rainfed (S) or irrigated (I) conditions.

4 | Discussion

Agricultural production is directly related to local weather conditions, which promote changes in crop growth and development. Due to the distinct climate characteristics of the semi-arid region of Brazil, agricultural crops require that strategies of adaptation and mitigation be adopted to provide favourable conditions for cultivation. It is therefore necessary to identify the local climate variables and consider the influence of non-climate factors that affect the sensitivity of the crop to the climate, for example, the importance of adopting agronomic strategies such as adjusting planting times (Moradi et al. 2013). In our study, we identified various planting times for forage cactus clones and sorghum cultivars under different planting densities, i.e., irrigated or rainfed, single or intercropped, with or without mulching, to improve sustainable forage production in the semi-arid region of Brazil.

4.1 | Productive Response of Cactus and Sorghum in Intercropping or Single Systems

Forage cactus and sorghum, when grown under an intercropping system, tend to have lower individual yields than when grown as single crops. However, when the intercropping systems were combined, greater productivity was observed in the intercropping system than in the single systems (Figure 3). This is directly related to the interspecific competition between crops in an intercropping system for available resources such as water, nutrients and light (Amorim et al. 2017; Makino et al. 2019; Alves et al. 2022). Jardim et al. (2021) noted that intercropping forage cactus with sorghum in semi-arid environments can increase natural resource use efficiency through interspecific complementarity. Morugán-Coronado et al. (2020) also noted that intercropping provides alternative supplies of pasture and contributes to food and economic security in the face of market volatility.

4.2 | Adaptability and Performance of Forage Cactus Clones in a Semi-Arid Environment

A productive analysis of the different cactus–sorghum systems (Figure 3) revealed that, in general, the OEM cactus clone tends to stand out in relation to the others, regardless of the cropping arrangement. This behaviour is attributed to the intrinsic characteristics of the genus *Opuntia*, which has fewer nutrient demands, is more tolerant of water deficit than are clones of the genus *Nopalea* (Inácio et al. 2020), and is the most cultivated genus in the world (Dubeux et al. 2021). Studies have confirmed the attributes of this genus, highlighting that OEMs have greater water use efficiency and biomass production than MIU and IPA (Araújo Júnior, Silva, Souza, Souza, et al. 2021; Silva et al. 2015), higher biometric values, and are less susceptible to mortality (Jardim et al. 2021).

This study focused on the main forage cactus clones from the Brazilian semi-arid region (OEM, MIU and IPA) because of their characteristics. However, the management practices adopted in this work, such as intercropping, supplementary irrigation and increased planting density, have the potential to be applied to other forage species adapted to semi-arid environments, such as sorghum, millet and elephant grass, which also have C4 metabolism and tolerance to water stress (Alves et al. 2022; Dubeux et al., 2021). The efficiency of OEMs in water use, for example, is a characteristic shared by other species of the genus *Opuntia*, indicating that similar results could be expected with other forage cactus (Queiroz et al. 2015; Jardim et al. 2021).

It is also worth noting that in other regions with greater or lower water availability, specific adjustments in management practices are necessary to ensure productive efficiency (Pereira et al. 2020; Lima, Silva, Pereira, et al. 2018). However, future studies that include a greater diversity of forage plant species and climatic conditions are recommended to broaden the generalizability of the results.

4.3 | Systems of Forage Crops Under Irrigated Conditions

In general, on the basis of the results observed, it was possible to observe from the agricultural calendar that planting at the beginning of the rainy season (December to January) is extremely important for increasing productivity under dry conditions, reducing the risk of losses due to water deficit. However, under irrigated conditions, flexibility in the planting calendar allows greater adaptation to variable climatic conditions, with planting periods with longer cycles and lower risks of losses (Lima, Silva, Jardim, et al. 2018; Silva et al. 2021).

On the basis of the simulations, the irrigated systems provided increases in productivity compared with those grown with no irrigation (Figure 4), which were found mainly in locations with relatively high temperatures and reduced rainfall. Irrigation maintains the availability and stability of soil water, favouring absorption by plants, in addition to a tendency to extend the period of cultivation and reduce the risk of loss (Campos et al. 2021; Nunes et al. 2021). Studies carried out in the semi-arid region of Brazil have also shown the importance of irrigation and its influence on increased productivity in forage cactus and sorghum grown individually and intercropped (Diniz et al. 2017; Lima, Silva, Jardim, et al. 2018; Jardim et al. 2021; Kumar et al. 2021). Dantas et al. (2023) highlighted the importance and adaptability of the forage cactus to regions with high water deficit but emphasised the need to supplement the water to achieve full productive development in places of low altitude, high temperatures and a small thermal range; this additional water requirement can vary between 2.5 and 7.5 mm per week. From knowledge of the use of irrigation to supplement water in the forage cactus, a trend was observed towards productive growth in the forage cactus for an increase in irrigation depth up to approximately 80% of the ETc, after which the trend was for growth to stabilise, i.e., even with a subsequent increase in irrigation depth, there was no significant increase in production (Pereira et al. 2020; Queiroz et al. 2015). Dubeux et al. (2021) reported that clones of the genus *Opuntia*, despite having lower concentrations of dry matter and soluble carbohydrates than *Nopalea*, exhibit lower nutrient demands and greater tolerance to drought, resulting in a better productive response under semi-arid conditions. This behaviour explains the superiority of the OEM clone in terms of biomass production in the semi-arid region of Brazil in relation to the other clones.

4.4 | Use of Mulch in Agricultural Systems With Pasture

When the effect of mulch on biomass production was analysed, better system performance was observed when mulch was used (Figure 4). The use of mulch to cultivate the forage cactus afforded better conditions for conserving water in the soil, reducing losses due to evaporation and soil temperature and, by means of plant decomposition, improving the physicochemical properties of the soil (Kader et al. 2017; Souza et al. 2021). Amorim et al. (2017) reported that mulching favours the emission of new cladodes. Therefore, the use of mulch has proven to be an effective practice for water conservation, especially in places with lower water demand, such as Garanhuns, where biomass production is maintained at levels similar to those of irrigated systems (Souza et al. 2021; Dantas et al. 2023).

4.5 | Plant Density Under Increased Land Use With Forage Plants

The increase in plant density resulted in an increase in biomass production at almost every location, especially under irrigation (Figure 4). Other studies with different densities reported similar behaviours (Souza et al. 2017; Dubeux et al. 2021; Alves et al. 2022). This shows that the importance of plant density in increasing biomass production per unit area is considerable, increasing land use efficiency and reducing areas of bare soil and, consequently, water loss through evaporation. Forage cactus clones present traits that differ in relation to the morphological characteristics of the cladodes, which are directly influenced by soil and climate conditions. Plants with smaller cladodes can optimise vertical growth, resulting in the formation of taller and narrower plants, as seen in the MIU clone, favouring plant density, with a consequent increase in the number of plants. On the other hand, plants with larger cladodes, such as the OEM clone, tend towards lateral growth due to their shape (Edvan et al. 2020).

4.6 | Sustainability of Agricultural Intensification

This study demonstrated that agricultural intensification, through practices such as supplementary irrigation, increased planting density and intercropping of forage plants, can significantly increase biomass production (up to 150% with irrigation and 140% with high density). However, it is important to consider broader dimensions of sustainability, such as water use efficiency, soil health and long-term economic viability. For example, Jardim et al. (2021) reported that intercropping forage cactus and sorghum can improve water use efficiency by up to 47%, whereas Sá Souza et al. (2022) reported that the use of mulch reduces water loss through evaporation by 30%, promoting greater soil moisture retention.

However, expanding irrigation, while increasing productivity, can increase water consumption by up to 80% in some regions, as observed by Diniz et al. (2017), which requires careful management to avoid wasting water resources. Furthermore, high-density planting can lead to soil nutrient depletion of up to 25% over time, as reported by Araújo Júnior, Silva, Souza, Souza, et al. (2021), requiring nutrient replacement practices to maintain soil health. Economic viability should also be considered, as smallholders may face high initial costs to implement irrigation systems, which can represent up to 40% of the total investment, according to Pinheiro et al. (2021).

Therefore, although agricultural intensification offers significant productivity benefits, it is essential to adopt balanced planning, integrating sustainable practices and supportive policies to ensure that productive gains do not compromise environmental health and socioeconomic viability in the long term.

5 | Conclusions

The AquaCrop model was able to simulate different cropping and agricultural management systems with forage crops, suggesting agricultural systems and calendars for different locations in the semi-arid region of Brazil. The model proved to be an important tool for estimating agricultural production and in decision-making. The cactus–sorghum intercropping system is an excellent option, increasing the supply of forage in addition to optimising the use of land and natural resources and providing nutritional balance on the basis of the quality of the forage. Cropping systems under irrigated conditions tended to increase the level of biomass production. In addition, under irrigated conditions, the risk of losses was lower than that under cultivation with no irrigation. The increased density of forage cactus and sorghum cultivated individually and as intercrops in semi-arid regions favours the optimisation of natural resources with better land use efficiency. Further studies are recommended to use the AquaCrop model for different forage crops and locations under different soil and climate conditions, allowing the process to be improved and, as a result, broadening its operational range geographically. Moreover, additional studies regarding the effects of pests and diseases on the productive response of crops are important, together with their influence on simulations via the AquaCrop model, since various regions are affected by these reducing factors.

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Data Availability Statement

Data available on request from the authors.

References

Adeboye, O. B., B. Schultz, A. P. Adeboye, K. O. Adekalu, and J. A. Osunbitan. 2021. "Application of the AquaCrop Model in Decision Support for Optimization of Nitrogen Fertilizer and Water Productivity of Soybeans." *Information Processing in Agriculture* 8, no. 3: 419–436. https://doi.org/10.1016/J.INPA.2020.10.002.

Allen, R. G., L. S. Pereira, D. Raes, M. Smith 1998. "Crop Evapotranspiration (Guidelines for Computing Crop Water Requirements)". FAO Irrigation and Drainage Paper N° 56.

Alvares, C. A., J. L. Stape, P. C. Sentelhas, and J. L. de Moraes Gonçalves. 2013. "Modeling Monthly Mean Air Temperature for Brazil." *Theoretical and Applied Climatology* 113, no. 3–4: 407–427. https://doi.org/10.1007/s00704-012-0796-6.

Alves, C. P., A. M. R. F. Jardim, G. N. Araújo Júnior, et al. 2022. "How to Enhance the Agronomic Performance of Cactus-Sorghum Intercropped System: Planting Configurations, Density and Orientation." *Industrial Crops and Products* 184: 115059. https://doi.org/10.1016/j.indcrop.2022.115059.

Amorim, D. M., T. G. F. Silva, P. C. Pereira, L. S. B. Souza, and R. B. Minuzzi. 2017. "Phenophases and Cutting Time of Forage Cactus Under Irrigation and Cropping Systems." *Pesquisa Agropecuária Tropical* 47, no. 1: 62–71. https://doi.org/10.1590/1983-40632016v4742746.

Araújo Júnior, G. D. N., T. G. F. Silva, L. S. B. Souza, et al. 2021. "Productivity, Bromatological Composition and Economic Benefits of Using Irrigation in the Forage Cactus Under Regulated Deficit Irrigation in a Semiarid Environment." *Bragantia* 80: 1–12. https://doi.org/10.1590/1678-4499.20200390.

Araújo Júnior, G. N., T. G. F. Silva, L. S. B. Souza, et al. 2021. "Phenophases, Morphophysiological Indices and Cutting Time in Clones of the Forage Cacti Under Controlled Water Regimes in a Semiarid Environment." *Journal of Arid Environments* 190: 104510. https://doi.org/10.1016/J.JARIDENV.2021.104510.

Araya, A., I. Kisekka, and J. Holman. 2016. "Evaluating Deficit Irrigation Management Strategies for Grain Sorghum Using AquaCrop." *Irrigation Science* 34, no. 6: 465–481. https://doi.org/10.1007/s00271-016-0515-7.

Bahmani, O., and S. Eghbalian. 2018. "Simulating the Response of Sugarcane Production to Water Deficit Irrigation Using the AquaCrop Model." *Agricultural Research* 7, no. 2: 158–166. https://doi.org/10.1007/s40003-018-0311-0.

Bell, L. W., A. D. Moore, and D. T. Thomas. 2018. "Integrating Diverse Forage Sources Reduces Feed Gaps on Mixed Crop-Livestock Farms." *Animal* 12, no. 9: 1967–1980. https://doi.org/10.1017/S1751731117003196.

Bello, Z. A., and S. Walker. 2016. "Calibration and Validation of AquaCrop for Pearl Millet (*Pennisetum glaucum*)." *Crop and Pasture Science* 67, no. 9: 948–960. https://doi.org/10.1071/CP15226.

Beza, E., J. V. Silva, L. Kooistra, and P. Reidsma. 2017. "Review of Yield Gap Explaining Factors and Opportunities for Alternative Data Collection Approaches." *European Journal of Agronomy* 82: 206–222. https://doi.org/10.1016/j.eja.2016.06.016.

Campos, A. R. F., A. J. P. Silva, Q. J. Lier, et al. 2021. "Yield and Morphology of Forage Cactus Cultivars Under Drip Irrigation Management Based on Soil Water Matric Potential Thresholds." *Journal of Arid Environments* 193: 104564. https://doi.org/10.1016/j.jaridenv.2021.104564.

Cooper, M., L. M. S. Mendes, W. L. C. Silva, and G. Sparovek. 2005. "A National Soil Profile Database for Brazil Available to International Scientists." *Soil Science Society of America Journal* 69, no. 3: 649–652. https://doi.org/10.2136/sssaj2004.0140.

Cunha, A. P. M., R. C. Alvalá, C. A. Nobre, and M. A. Carvalho. 2015. "Monitoring Vegetative Drought Dynamics in the Brazilian Semiarid Region." *Agricultural and Forest Meteorology* 214–215: 494–505. https://doi.org/10.1016/J.AGRFORMET.2015.09.010.

Dantas, F. D. G., M. V. F. Santos, G. F. C. Lima, J. J. Coêlho, J. F. Medeiros, and M. V. Cunha. 2023. "Drip Irrigation With Saline Water Combined With Mulch Cover as Strategies for Forage Cactus Production in Semi-Arid Zones." *Irrigation Science* 41, no. 2: 295–308. https://doi.org/10.1007/S00271-022-00841-8/FIGURES/3.

Dias, H. B., and P. C. Sentelhas. 2018. "Sugarcane Yield Gap Analysis in Brazil—A Multi-Model Approach for Determining Magnitudes and Causes." *Science of the Total Environment* 637: 1127–1136. https://doi.org/10.1016/j.scitotenv.2018.05.017.

Diniz, W. J. S., T. G. F. Silva, J. M. S. Ferreira, et al. 2017. "Forage Cactus-Sorghum Intercropping at Different Irrigation Water Depths in the Brazilian Semiarid Region." *Pesquisa Agropecuária Brasileira* 52, no. 9: 724–733. https://doi.org/10.1590/s0100-204x2017000900004.

Dubeux, J. C. B., M. V. F. Santos, M. V. Cunha, et al. 2021. "Cactus (*Opuntia* and *Nopalea*) Nutritive Value: A Review." *Animal Feed Science and Technology* 275: 114890. https://doi.org/10.1016/j.anifeedsci.2021.114890.

Edvan, R. L., R. R. M. Mota, T. P. Dias-Silva, et al. 2020. "Resilience of Cactus Pear Genotypes in a Tropical Semi-Arid Region Subject to Climatic Cultivation Restriction." *Scientific Reports* 10, no. 1: 10040. https://doi.org/10.1038/s41598-020-66972-0.

Farooq, N., and S. H. Gheewala. 2020. "Assessing the Impact of Climate Change on Sugarcane and Adaptation Actions in Pakistan." *Acta Geophysica* 68, no. 5: 1489–1503. https://doi.org/10.1007/s11600-020-00463-8.

Giménez, L., P. Paredes, and L. S. Pereira. 2017. "Water Use and Yield of Soybean Under Various Irrigation Regimes and Severe Water Stress. Application of AquaCrop and SIMDualKc Models." *Water* 9, no. 6: 393. https://doi.org/10.3390/W9060393.

Guo, D. X., C. F. Chen, P. Y. Guo, X. Y. Yuan, X. G. Xing, and X. Y. Ma. 2018. "Evaluation of AquaCrop Model for Foxtail Millet (*Setaria Italica*) Growth and Water Use With Plastic Film Mulching and No Mulching Under Different Weather Conditions." *Water (Switzerland)* 10, no. 7: 836. https://doi.org/10.3390/w10070836.

Hadebe, S. T., A. T. Modi, and T. Mabhaudhi. 2017. "Calibration and Testing of Aquacrop for Selected Sorghum Genotypes." *Water SA* 43, no. 2: 209. https://doi.org/10.4314/wsa.v43i2.05.

Heng, L. K., T. Hsiao, S. Evett, T. Howell, and P. Steduto. 2009. "Validating the FAO Aquacrop Model for Irrigated and Water Defi Cient Field Maize." *Agronomy Journal* 101, no. 3: 488–498. https://doi.org/10.2134/agronj2008.0029xs.

Hsiao, T. C., L. Heng, P. Steduto, B. Rojas-Lara, D. Raes, and E. Fereres. 2009. "AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: III. Parameterization and Testing for Maize." *Agronomy Journal* 101, no. 3: 448–459. https://doi.org/10.2134/agronj2008.0218s.

Inácio, J. G., M. G. Conceição, D. C. Santos, et al. 2020. "Nutritional and Performance Viability of Cactus *Opuntia*-Based Diets With Different Concentrate Levels for Girolando Lactating Dairy Cows." *Asian-Australasian Journal of Animal Sciences* 33, no. 1: 35. https://doi.org/10.5713/AJAS.18.0916.

Jardim, A. M. R. F., T. G. F. Silva, L. S. B. Souza, et al. 2021. "Intercropping Forage Cactus and Sorghum in a Semi-Arid Environment Improves Biological Efficiency and Competitive Ability Through Interspecific Complementarity." *Journal of Arid Environments* 188: 104464. https://doi.org/10.1016/j.jaridenv.2021.104464.

Jardim, A. M. R. F., T. G. F. Silva, L. S. B. Souza, and M. S. Souza. 2020. "Interaction of Agroecosystem Intercropped With Forage Cactus-Sorghum in the Semi-Arid Environment: A Review." *Journal* *of Environmental Analysis and Progress* 5, no. 1: 69. https://doi.org/10.24221/jeap.5.1.2020.2743.069-087.

Kader, M. A., M. Senge, M. A. Mojid, and K. Ito. 2017. "Recent Advances in Mulching Materials and Methods for Modifying Soil Environment." *Soil and Tillage Research* 168: 155–166. https://doi.org/10.1016/J.STILL.2017.01.001.

Kumar, S., M. Louhaichi, P. Dana Ram, et al. 2021. "Cactus Pear (*Opuntia ficus-indica*) Productivity, Proximal Composition and Soil Parameters as Affected by Planting Time and Agronomic Management in a Semi-Arid Region of India." *Agronomy* 11, no. 8: 1647. https://doi.org/10.3390/AGRONOMY11081647.

Lima, L. R., T. G. F. Silva, A. M. R. F. Jardim, C. A. A. Souza, M. G. Queiroz, and J. N. Tabosa. 2018. "Growth, Water Use and Efficiency of Forage Cactus Sorghum Intercropping Under Different Water Depths." *Revista Brasileira de Engenharia Agricola e Ambiental* 22, no. 2: 113–118. https://doi.org/10.1590/1807-1929/AGRIAMBI.V22N2P113-118.

Lima, L. R., T. G. F. Silva, P. D. C. Pereira, J. E. F. Morais, and M. C. D. S. Assis. 2018. "Productive-Economic Benefit of Forage Cactus–Sorghum Intercropping Systems Irrigated With Saline Water." *Revista Caatinga* 31, no. 1: 191–201. https://doi.org/10.1590/1983-21252018v31n122rc.

Linker, R., I. Ioslovich, G. Sylaios, F. Plauborg, and A. Battilani. 2016. "Optimal Model-Based Deficit Irrigation Scheduling Using AquaCrop: A Simulation Study With Cotton, Potato and Tomato." *Agricultural Water Management* 163: 236–243. https://doi.org/10.1016/j.agwat.2015.09.011.

Magalhães, I. D., G. B. Lyra, J. L. Souza, et al. 2019. "Performance of the AquaCrop Model for Bean (*Phaseolus Vulgaris* L.) Under Irrigation Condition." *Australian Journal of Crop Science* 13, no. 7: 1188–1196. https://doi.org/10.21475/ajcs.19.13.07.p1790.

Makino, P. A., G. Ceccon, and R. Fachinelli. 2019. "Produtividade e teor de nutrientes em populações de milho safrinha solteiro e consorciado com braquiária." *Revista Brasileira de Milho e Sorgo* 18, no. 2: 206–220. https://doi.org/10.18512/1980-6477/rbms.v18n2p206-220.

Monteiro, L. A., A. M. Allee, E. E. Campbell, et al. 2020. "Assessment of Yield Gaps on Global Grazed-Only Permanent Pasture Using Climate Binning." *Global Change Biology* 26, no. 3: 1820–1832. https://doi.org/10.1111/gcb.14925.

Moradi, R., A. Koocheki, M. N. Mahallati, and H. Mansoori. 2013. "Adaptation Strategies for Maize Cultivation Under Climate Change in Iran: Irrigation and Planting Date Management." *Mitigation and Adaptation Strategies for Global Change* 18, no. 2: 265–284. https://doi.org/10.1007/S11027-012-9410-6/FIGURES/7.

Moraes, G. S. O., A. Guim, J. N. Tabosa, J. C. C. Chagas, M. P. Almeida, and M. A. Ferreira. 2019. "Cactus [*Opuntia Stricta* (Haw.) Haw] Cladodes and Corn Silage: How Do We Maximize the Performance of Lactating Dairy Cows Reared in Semiarid Regions?" *Livestock Science* 221: 133–138. https://doi.org/10.1016/j.livsci.2019.01.026.

Morugán-Coronado, A., C. Linares, M. D. Gómez-López, Á. Faz, and R. Zornoza. 2020. "The Impact of Intercropping, Tillage and Fertilizer Type on Soil and Crop Yield in Fruit Orchards Under Mediterranean Conditions: A Meta-Analysis of Field Studies." *Agricultural Systems* 178, no. November 2019: 102736. https://doi.org/10.1016/j.agsy.2019.102736.

Nunes, H. G. G. C., V. D. S. Farias, D. P. Sousa, et al. 2021. "Parameterization of the AquaCrop Model for Cowpea and Assessing the Impact of Sowing Dates Normally Used on Yield." *Agricultural Water Management* 252: 106880. https://doi.org/10.1016/j.agwat.2021.106880.

Pereira, J. S., A. B. Cavalcante, G. H. M. S. M. F. Nogueira, et al. 2020. "Morphological and Yield Responses of Spineless Cactus Orelha de Elefante Mexicana Under Different Cutting Intensities." *Revista Brasileira de Saúde e Produção Animal* 21: 1–10. https://doi.org/10.1590/s1519-99402121142020.

Pessoa, D. V., A. P. Andrade, A. L. R. Magalhães, et al. 2020. "Forage Nutritional Differences Within the Genus *Opuntia*." *Journal of Arid Environments* 181: 104243. https://doi.org/10.1016/j.jaridenv.2020.104243.

Pinheiro, A. G., C. P. Alves, C. A. A. Souza, et al. 2024. "Calibration and Validation of the Aquacrop Model for Production Arrangements of Forage Cactus and Grass in a Semi-Arid Environment." *Ecological Modelling* 488: 110606. https://doi.org/10.1016/j.ecolmodel.2023.110606.

Pinheiro, A. G., L. S. B. Souza, A. M. R. F. Jardim, et al. 2021. "Lacunas de produtividades e estratégias de cultivo na melhoria da produção de forragem para a região semiárida brasileira - Revisão." *Revista Brasileira De Geografia Física* 14, no. 4: 2403–2426. https://doi.org/10.26848/rbgf.v14.4.p2403-2426.

Queiroz, M. G., T. G. F. Silva, S. Zolnier, S. M. S. Silva, L. R. Lima, and J. O. Alves. 2015. "Características morfofisiológicas e produtividade da palma forrageira em diferentes lâminas de irrigação." *Revista Brasileira de Engenharia Agricola e Ambiental* 19, no. 10: 931–938. https://doi.org/10.1590/1807-1929/AGRIAMBI.V19N10P931-938.

Raes, D., P. Steduto, T. C. Hsiao, and E. Fereres. 2009. "AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: II. Main Algorithms and Software Description." *Agronomy Journal* 101, no. 3: 438–447. https://doi.org/10.2134/agronj2008.0140s.

Razzaghi, F., Z. Zhou, M. N. Andersen, and F. Plauborg. 2017. "Simulation of Potato Yield in Temperate Condition by the AquaCrop Model." *Agricultural Water Management* 191: 113–123. https://doi.org/10.1016/j.agwat.2017.06.008.

Sá Souza, M., G. N. A. Júnior, L. S. B. Souza, et al. 2022. "Forage Yield, Competition and Economic Benefit of Intercropping Cactus and Millet With Mulch in a Semi-Arid Environment." *African Journal of Range & Forage Science* 40: 219–230. https://doi.org/10.2989/10220119.2021.2016967.

Saab, M. T. A., R. Albrizio, V. Nangia, F. Karam, and Y. Rouphael. 2014. "Developing Scenarios to Assess Sunflower and Soybean Yield Under Different Sowing Dates and Water Regimes in the Bekaa Valley (*Lebanon*): Simulations With Aquacrop." *International Journal of Plant Production* 8: 1735–6814. https://hdl.handle.net/20.500.11766/7314.

Santos, R. D., K. J. Boote, L. E. Sollenberger, et al. 2017. "Simulated Optimum Sowing Date for Forage Pearl Millet Cultivars in Multilocation Trials in Brazilian Semi-Arid Region." *Frontiers in Plant Science* 8: 2074. https://doi.org/10.3389/fpls.2017.02074.

Sentelhas, P. C., R. Battisti, G. M. S. Câmara, J. R. B. Farias, A. C. Hampf, and C. Nendel. 2015. "The Soybean Yield Gap in Brazil—Magnitude, Causes and Possible Solutions for Sustainable Production." *Journal of Agricultural Science* 153, no. 8: 1394–1411. https://doi.org/10.1017/S0021859615000313.

Silva, T. G. F., J. T. Araújo Primo, J. E. F. Morais, W. J. S. Diniz, C. A. A. Souza, and M. C. Silva. 2015. "Crescimento e produtividade de clones de palma forrageira no Semiárido e relações com variáveis meteorológicas." *Revista Caatinga* 28, no. 2: 10–18.

Silva, T. G. F., M. G. Queiroz, S. Zolnier, et al. 2021. "Soil Properties and Microclimate of Two Predominant Landscapes in the Brazilian Semiarid Region: Comparison Between a Seasonally Dry Tropical Forest and a Deforested Area." *Soil and Tillage Research* 207: 104852. https://doi.org/10.1016/j.still.2020.104852.

Souza, M. D. S., T. G. F. Silva, L. S. B. Souza, et al. 2021. "Growth, Phenology and Harvesting Time of Cactus-Millet Intercropping System Under Biotic Mulching." *Archives of Agronomy and Soil Science* 68, no. 6: 764–778. https://doi.org/10.1080/03650340.2020.1852553.

Souza, T. C., M. V. F. Santos, J. C. B. Dubeux Júnior, et al. 2017. "Productivity and Nutrient Concentration in Spineless Cactus Under Different Fertilizations and Plant Densities." *Revista Brasileira de*

Ciências Agrárias - Brazilian Journal of Agricultural Sciences 12, no. 4: 555–560. https://doi.org/10.5039/agraria.v12i4a5473.

Steduto, P., T. C. Hsiao, D. Raes, and E. Fereres. 2009. "AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles." *Agronomy Journal* 101, no. 3: 426–437. https://doi.org/10.2134/agronj2008.0139s.

Van Gaelen, H., A. Tsegay, N. Delbecque, et al. 2015. "A Semi-Quantitative Approach for Modelling Crop Response to Soil Fertility: Evaluation of the AquaCrop Procedure." *Journal of Agricultural Science* 153, no. 7: 1218–1233. https://doi.org/10.1017/S0021859614000872.

Veloso, G. A., M. E. Ferreira, L. G. Ferreira Júnior, and B. B. Silva. 2020. "Modelling Gross Primary Productivity in Tropical Savanna Pasturelands for Livestock Intensification in Brazil." *Remote Sensing Applications: Society and Environment* 17: 100288. https://doi.org/10.1016/j.rsase.2020.100288.

Zhang, Z., M. Christensen, Z. Nan, et al. 2019. "Plant Development and Solar Radiation Interception of Four Annual Forage Plants in Response to Sowing Date in a Semi-Arid Environment." *Industrial Crops and Products* 131: 41–53. https://doi.org/10.1016/j.indcrop.2019.01.028.

Zhu, X., K. Xu, Y. Liu, R. Guo, and L. Chen. 2021. "Assessing the Vulnerability and Risk of Maize to Drought in China Based on the AquaCrop Model." *Agricultural Systems* 189: 103040. https://doi.org/10.1016/j.agsy.2020.103040.