ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.29, n.8, e289895, 2025
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

ORIGINAL ARTICLE

Agrometeorological modeling of the forage cactus cultivar *Opuntia stricta* (Haw.) Haw in different irrigation frequencies[1]

Modelagem Agrometeorológica da palma forrageira cultivar *Opuntia stricta* (Haw.) Haw em diferentes frequências de irrigação

Jaciara R. Miranda[2], Dermeval A. Furtado[2*], Valquiria C. da Silva[2], Airton G. de Oliveira[3] & Vicente de P. R. da Silva[2]

[1] Research developed at Instituto Nacional do Semiárido, Campina Grande, PB, Brazil
[2] Universidade Federal em Campina Grande, Campina Grande, PB, Brazil
[3] Universidade Federal do Maranhão, Chapadinha, MA, Brazil

HIGHLIGHTS:
AquaCrop accurately estimates the yield of Opuntia stricta *(Haw.) Haw.*
AquaCrop accurately estimates biomass value/field yield.
Modeling stands out as an important agricultural tool.

ABSTRACT: The objective with this research was to calibrate and validate the AquaCrop model for the forage cactus cultivar *Opuntia stricta* (Haw.) Haw, in order to simulate crop yield and make the model applicable to the simulation of yield in the semiarid region. The AquaCrop model version 5.0 has four modules, which cover aspects related to climate, crop, irrigation and soil and, these modules were fed with the data collected in an experiment carried out at the Experimental Farm of the National Institute of the Semiarid (INSA), located in the municipality of Campina Grande city, PB, in the mesoregion of Agreste, Brazil. Based on these data, yield estimation was carried out, observing the effect of water on crop yield. To validate the model, the data obtained in the field at the irrigation frequencies of 7 and 28 days were compared with the results estimated by the AquaCrop model. The calibration and validation of the AquaCrop model for the forage cactus cultivar *Opuntia stricta* (Haw.) Haw, presented satisfactory results for the simulated productivity when compared to the yield obtained in the field for the irrigation frequencies of 7 and 28 days, making AquaCrop a model applicable to the simulation of yield and responses to water stress of these crops, which can assist the producer in the decision-making process on his property.

Key words: AquaCrop model, water use efficiency, yield

RESUMO: O objetivo com esta pesquisa foi calibrar e validar o modelo AquaCrop para a palma forrageira cultivar *Opuntia stricta* (Haw.) Haw, a fim de simular a produtividade da cultura e tornar o modelo aplicável à simulação de produtividade na região semiárida. O modelo AquaCrop versão 5.0 possui quatro módulos, que abrangem aspectos relacionados ao clima, cultura, irrigação e solo e, estes módulos foram alimentados com os dados coletados em um experimento realizado na Fazenda Experimental do Instituto Nacional do Semiárido (INSA), localizada no município de Campina Grande, PB, na mesorregião do Agreste. Com base nestes dados, foi realizada a estimativa da produtividade, observando o efeito da água na produtividade da cultura. Para validar o modelo, os dados obtidos em campo nas frequências de irrigação de 7 e 28 dias foram comparados com os resultados estimados pelo modelo AquaCrop. A calibração e validação do modelo AquaCrop para a palma forrageira cultivar *Opuntia stricta* (Haw.) Haw, apresentou resultados satisfatórios para a produtividade simulada quando comparada à produtividade obtida em campo para as frequências de irrigação de 7 e 28 dias, tornando o AquaCrop um modelo aplicável à simulação de produtividade e respostas ao estresse hídrico dessas culturas, podendo auxiliar o produtor no processo de tomada de decisão em sua propriedade.

Palavras-chave: modelo AquaCrop, eficiência no uso de água, produtividade

• Ref. 289895 – Received 30 Aug, 2024
* Corresponding author - E-mail: araujodermeval@gmail.com
• Accepted 05 Feb, 2025 • Published 27 Feb, 2025
Editors: Antônio Gustavo de Luna Souto & Carlos Alberto Vieira de Azevedo

Introduction

The forage cactus cultivar *Opuntia stricta* (Haw.) Haw has emerged as an alternative for the semiarid region, as it is adapted to the climate due to its anatomical, morphological and physiological characteristics, such as its high efficiency in water use due to its form of CO_2 assimilation through the acid metabolism of Crassulaceans (CAM), which makes it an important forage resource for livestock in the region (Souza et al., 2018).

To increase production and yield and ensure the longevity of forage cactus in these regions, several technologies can be used, including irrigation. Low-volume irrigation promotes changes in the growth dynamics of this crop and in its metabolism, which gradually changes from the acid metabolism of Crassulaceans (CAM) to the C3 metabolism, acting as a facultative CAM, increasing yield and quality, standardizing plant development and reducing the effect of seasonality in production (Miranda et al., 2023).

Field and controlled environment research is carried out to evaluate the productivity of forage cactus associated with different irrigation management methods, but they are more laborious and costlier. Therefore, crop modeling stands out as an important agricultural tool for studying and developing irrigation strategies, estimating the water needs of the crop throughout the cycle and its productive potential in different climate scenarios. This facilitates decision-making on the management of factors that affect its production (Alves et al., 2020).

Among the existing crop modeling models, AquaCrop model stands out for its accuracy, simplicity, robustness and ease of use. It was developed by FAO (Allen et al., 1998) and is driven by soil water balance, which is an extremely important factor in crop water stress responses (Raes et al., 2009).

Modeling in agriculture has been successful for several crops, such as soybean -*Glycine max* (Barrera Junior et al., 2024); cotton - *Gossypium barbadense* (Du et al., 2024), potato - *Solanum tuberosum* (Zhou et al., 2018) and, corn - *Zea mays* (Sharafkhane et al., 2024). However, due to the lack of studies on cactus pear and considering its gradual transition from CAM metabolism to C3 metabolism, acting as a facultative CAM when irrigated. In semiarid regions, climate change and population growth can lead to the collapse of water resource availability, with the agricultural sector being the most affected. In an attempt to assist in food security and assess the effect of the environment and management on agricultural production, the AquaCrop model was developed, an agroclimatic tool that allows measuring the effect of climate conditions on productive performance and the decline in productivity of agricultural crops under different water conditions (Dantas et al., 2024).

The hypothesis of this study is that with the production of forage cactus at different irrigation frequencies, agrometeorological factors directly influence the result of the modeling with AquaCrop. Given the context, the objective of this research was to calibrate and validate the AquaCrop model for the forage cactus cultivar *Opuntia stricta* (Haw.) Haw, in order to simulate crop productivity and make the model applicable to productivity simulation in the semiarid region, assisting producers in decision-making.

Material and Methods

The experiment took place at the Experimental Farm of the National Institute of the Semiarid (INSA), located in the municipality of Campina Grande city, PB, Brazil, in the mesoregion of Agreste, whose coordinates are South latitude 07° 14' 00" and West longitude 35° 57' 00", with an altitude of 491 m, and the climate of the region classified as As according to the Köppen classification (Alvares et al., 2013). The experimental period was 12 months, comprising the first year of the cactus cycle (January to December 2020).

The total experimental area was 9.45 m², using the same spacing between plants and plant density (Table 1) for drip irrigation frequencies of 7 and 28 days. The appropriate temperature used for forage cactus was proposed by Bezerra et al. (2014) and the root depth was established according to Edvan et al. (2013). The experimental period lasted 12 months, comprising the first year of the forage cactus cycle. The observed productivity was higher for plants irrigated at a frequency of 7 days when compared to plants irrigated at a frequency of 28 days (Table 1).

Two irrigation frequencies were used (7 and 28 days) in four blocks, with each treatment being repeated three times within the block (triplicate), totaling 24 experimental plots. Irrigation management for forage palms irrigated every 7 days was carried out using a weekly fixed depth of 8.74 mm, which corresponds to 35.96 mm per month, which is a complement to weekly precipitation, that is, if the volume of rainfall had been equal to or greater than necessary, weekly irrigation was discarded; otherwise, it was carried out. For the experimental plots irrigated every 28 days, the volume of 8.74 mm was used, which was distributed every 28 days. The water analysis obtained a C1 classification (Table 2), which corresponds to water with low salinity and adequate sodicity (Bernardo, 1995).

According to the Soil Taxonomy of the Soil Survey Staff (2022), the soil in the experimental area is classified as Palexeralfo Haplico, with a granulometry of 82.16% sand, 16.08% silt and 1.76% clay, with a sandy clayey texture and average porosity of 50% (Table 3). These soils are predominantly shallow, making water infiltration difficult, but forage cactus adapts well since the forage does not tolerate excess moisture in the soil (Alves et al., 2020).

The use of modeling in forage cactus through AquaCrop model was possible through the discovery that forage cactus

Table 1. Data on the forage cactus cultivar *Opuntia stricta* (Haw.) Haw in the experimental period

	7 days	28 days
Area (ha)	0.000945	0.000945
Plant spacing (m)	0.5	0.5
Plant density (plants ha^{-1})	19,047	19,047
Ideal temperature (°C)	18 to 32	18 to 32
Root depth (cm)	35	40
Time from transplanting to cutting (days)	366	366
Transplant recovery (days)	14	14
Observed yield (ton ha^{-1})	16.8837	14.3243

Table 2. Irrigation water analysis

pH	7.54
Electrical conductivity (μS m^{-1})	200
Calcium (meq L^{-1})	0.88
Magnesium (meq L^{-1})	0.48
Sodium (meq L^{-1})	0.54
Potassium (meq L^{-1})	0.05
Carbonates (meq L^{-1})	0.00
Bicarbonates (meq L^{-1})	0.80
Chlorides (meq L^{-1})	0.50
Sulfates (meq L^{-1})	Absent
Sodium Adsorption Ratio (RAS)	0.65
Water class	C1

Table 3. Chemical-physical-hydric characterization of soil

Chemical Characteristics	
Ca^{2+} (meq 100^{-1} g of soil)	1.85
Mg^{2+} (meq 100^{-1} g of soil)	2.54
Na^{+} (meq 100^{-1} g of soil)	0.17
K^{+} (meq /100^{-1} g of soil)	0.49
S (meq 100^{-1} g of soil)	5.05
H^{+} (meq 10^{-1} g of soil)	0.40
Al^{3+} (meq 100^{-1} g of soil)	0.24
CCQ	Absence
CO (%)	0.78
MO (%)	1.34
N (%)	0.08
P assimilable (mg /100^{-1} g of soil)	0.18
pH H_2O (1:2,5)	5.57
pH KCl (1:2,5)	5,05
CE – (mmhos /cm^{-1}) (Soil-Water Suspension)	0.16
pH (Saturation extract)	5.05
CE (mmhos/ cm^{-1})	0.59
Chloride (meq /L^{-1})	3.75
Carbonate (meq/ L^{-1})	0.00
Bicarbonate (meq L^{-1}meq/L)	0.40
Sulfate (meq L^{-1}meq/L)	Absence
Ca^{2+} (meq L^{-1}meq/L)	2.00
Mg^{2+} (meq L^{-1}meq/L)	1.25
K^{+} (meq L^{-1}meq/L)	0.55
Na^{+} (meq L^{-1}meq/L)	2.40
Percentage saturation	21.66
Sodium adsorption ratio	1.88
Salinity	Non-saline
Soil class	Normal
Physical Characteristics	
Sand (%)	82.16
Silt (%)	16.08
Clay (%)	1.76
Texture	Loamy sand
DS (g cm^{-3})	1.34
DP g cm^{-3}	2.68
Porosity %	50.00
Humidity (% dry soil base)	
Natural	0.54
0.10 atm	
0.33 atm	13.01
1.00 atm	
5.00 atm	
10.0 atm	
150 atm	5.62
WA	7.39

Ca^{2+} – Calcium; Mg^{2+} – Magnesium; Na^{+} – Sodium; K^{+} – Potassium; S – Sulfur; H^{+} – Hydrogen; Al^{3+} – Aluminum; CCQ – Qualitative calcium carbonate; CO - Organic carbon; MO - Organic matter; N – Nitrogen; P – Phosphorus; CE – Electrical conductivity; DS – Soil bulk density; DP - Particle density, and WA- water available

under water stress has high efficiency in water use, mainly due to its way of assimilating CO_2 through the crassulacean acid metabolism (CAM), a photosynthetic process that results in water savings due to stomatal closure during the day and opening at night (Miranda et al., 2023).

Thus, when subject to greater water availability, they gradually transition from CAM metabolism to C3 metabolism, acting as facultative CAM, thus causing a reduction in leaf temperature, an adjustment that provides a competitive advantage for CAM plants in dry environments when compared to other forage plants. Presenting higher internal CO_2 concentration; CO_2 uptake rate; instantaneous water use efficiency; intrinsic water use efficiency; instantaneous carboxylation efficiency at an irrigation frequency of every 7 days (Miranda et al., 2023).

The AquaCrop model, version 5.0, has four modules, including climate, crop, irrigation and soil. The climate aspects evaluated by the model are maximum and minimum temperatures (°C), average relative air humidity (%), precipitation (mm), wind speed (m s^{-1}) and sunlight (h). These modules included data collected in the experiment carried out at the Experimental Farm of the National Institute of Semiarid Region (INSA), located in the mesoregion of Agreste Paraibano. Based on these data, the model estimated productivity by observing the effect of water on crop yield, using Eqs. 1 and 2:

$$B = WP \times \sum Tr \tag{1}$$

$$Y = B \times HI \tag{2}$$

where:

WP - water productivity (kg m^{-2} mm^{-1});
Tr - transpiration of crop (mm);
B - dry biomass of the aerial part (kg);
Y - final yield (kg); and,
HI - harvest index (%).

The climate module was fed with daily meteorological data on maximum and minimum temperatures (°C), average relative air humidity (%), precipitation (mm), wind speed (m s^{-1}) and sunlight (hours) for the experimental year, collected at the automatic meteorological station of the National Institute of Meteorology (INMET) of the Federal Government, located in the municipality of Campina Grande city, Paraíba state, Brazil.

The crop module included the characteristics of the experiment and the forage cactus cultivar *Opuntia stricta* (Haw.) Haw, experimental area, plant density per hectare (plants ha^{-1}); spacing between plants (m), root depth (cm), crop maturity date (days), cutting date (days), yield obtained (ton ha^{-1}); and ideal temperature for the crop (°C).

The non-destructive estimate (without cutting) of the green matter biomass of the forage cactus was quantified in grams, based on Eq. 3.

$$BMVC = C \times W \times E \times 0.535 \tag{3}$$

where:

BMVC - green matter biomass of the cladode in g;
C - average length of the cladodes in cm;
W - average width of cladodes in cm; 25

E - average thickness of cladodes in cm; and,

0.535 - Factor resulting from the multiplication of the area correction factor (0.883) by the corrected specific weight (0.772 g cm^{-3}), by the value of 3.14 and by ¼, resulting from the calculation of the area of the ellipse, in g cm^{-3}.

Morphometric analyses of forage cactus were performed on four plants from each experimental plot, by assessing the monthly vegetative growth of the morphometric variables height (cm), width (cm) and thickness (cm) of the mother cactus and primary, secondary and tertiary cladodes, determined with the aid of a tape measure and digital caliper, considering from the ground to the highest end of the article, in addition to assessing the number of primary (u), secondary and tertiary cladodes through direct counting on the plant.

The irrigation module was fed with data on the irrigation frequencies used in the experimental period (I7 - irrigated at a frequency of 7 days and I28 - irrigated at a frequency of 28 days), as well as the dates on which drip irrigation was carried out (days), volume applied for each frequency (mm) and water quality.

In the soil module, information on soil moisture, soil type, percentage of soil cover by mulch (dead leaves, branches, etc.) was entered. The soil fertility was considered near optimal (90%) and since the areas were in no-tillage practice, the soil cover by mulches was fixed in 100% of unincorporated plant residues.

The performance of the AquaCrop model was validated by comparing the data obtained in the field in the treatments irrigated at frequencies of 7 and 28 days during the experiment in the first cycle of the forage cactus with the results estimated by AquaCrop model, using the following statistical parameters:

- Root mean square error (RMSE), defined by Eq. 4 (Raes et al., 2009):

$$RMSE = \frac{1}{\bar{O}_i}\sqrt{\frac{\sum_{i-1}^{N}(S_i - O_i)^2}{N}} \times 100 \quad (4)$$

where:

S_i and O_i - simulated and observed values, respectively;

O_i - average value of O_i; and,

N - number of observations.

- Normalized root mean square error (NRMSE) (Eq. 5) (Jiménez et al., 2013):

$$NRMSE = \frac{1}{\bar{O}_i}\sqrt{\frac{\sum(S_i - O_i)^2}{n}} \times 100 \quad (5)$$

where:

S_i and O_i - simulated and observed values, respectively;

O_i - average value of O_i; and,

n - number of observations.

- Willmott's Index of Agreement (d) (1982), defined by Eq. 6:

$$d = 1 - \frac{\sum_{i-1}^{N}(S_i - O_i)^2}{\sum\left(\left|S_i - \bar{O}_i\right| + \left|O_i - \bar{O}_i\right|\right)} \quad (6)$$

where:

S_i and O_i - simulated and observed values, respectively;

O_i - average value of O_i; and,

N - number of observations.

- Nash-Sutcliffe model efficiency coefficient (EF) (Eq. 7) (Jiménez et al., 2013):

$$EF = 10\frac{\sum(S_i - O_i)^2}{\sum(O_i - \bar{O}_i)^2} \quad (7)$$

where:

S_i and O_i - simulated and observed values, respectively; and,

O_i - average value of O_i.

- Prediction error (PE) (Eq. 8):

$$PE = \frac{\sum(S_i - O_i)}{\left(\sum O_i\right)} \times 100 \quad (8)$$

where:

S_i and O_i - simulated and observed values, respectively; and,

O_i - average value of O_i.

Thus, when the Nash-Sutcliffe model efficiency coefficient (EF) and Wilmott's index of agreement (d) approach to 1, and the prediction error (PE) and normalized root mean square error (NRMSE) approach to 0%, it implies that the model's performance was positive. In terms of simulation, it is considered excellent when NRMSE is less than 10%, good when NRMSE is between 10 and 20%, reasonable when NRMSE is between 20 and 30%; and bad when it is above 30%.

The calibration and validation of the model are determined through data from the crop under study, considering water use in the vegetative phases, with the model's performance being evaluated using the following statistical parameters: a) prediction error; b) efficiency coefficient; c) mean error; d) Willmott index (Rosa et al., 2020). Yield prediction through modeling is an ally in agriculture, aiming at efficient and sustainable production. Accurate predictions are important for farmers' decision-making regarding planting, irrigation, fertilization, harvesting, and marketing (Leukel et al., 2023).

Results and Discussion

Air temperature ranged from 20.75 to 30.23 °C, remaining within the appropriate range for the crop, which is 18 to 32 °C (Bezerra et al., 2014). The relative humidity of the air was above the recommended range for the development of the crop, which is from 37.3 to 63.1% (Souza et al., 2018), as well as wind speed, for which the ideal range should be between 1 and 3 m s^{-1} (Silva et al., 2020). The average insolation was 7.66 hours and the rainfall were also within what is considered adequate for the cultivation of forage cactus (Souza et al., 2018), between 368.4 and 812.4 mm per year (Table 4).

In the AquaCrop estimate, yield was well represented, that is, the model simulated the results for yield well, with an excellent approximation between the real yield values (Y) and those estimated, with minimal difference in the model's underestimation (Table 5).

The results indicate that the model has excellent performance for forage cactus cultivation with water availability influencing productivity, which was higher when there was less space between irrigation days. The difference in yield was 0.23 ton ha^{-1} for plants under irrigation frequency of 7 days and 0.50 ton ha^{-1} for those under 28 days (Table 6).

Thus, it is observed that as the treatments receive less water, the difference between the observed and estimated values increases, although forage cactus is not sensitive to water deficit. Thus, water availability in the plant improves the model's performance, as observed by Sharafkhane et al. (2024) when performing agrometeorological modeling of maize in AquaCrop model.

The root mean square error (RMSE) and prediction error (PE) showed values of 0.33 and 0.60 for yield, respectively, indicating that the model had excellent performance for forage cactus, due to the proximity between the observed and estimated values. As for the normalized root mean square error (NRMSE), the yield value was 2.11%, and the simulation was considered excellent, since the values are below 10% (Table 7).

The Nash-Sutcliffe model efficiency coefficient (EF) and Willmott's index of agreement (d) evaluated the model's performance as excellent, as the values were 0.89 and 0.98, respectively, and the closer to one, the better the result of these indices.

Table 4. Annual meteorological data from the experimental period

Meteorological Data	Annual average
Maximum air temperature (°C)	30.23
Average air temperature (°C)	24.15
Minimum air temperature (°C)	20.75
Relative air humidity (%)	77.60
Wind speed (m s^{-1})	3.18
Insolation (hours)	7.66
Total precipitation (mm)	551.20

Source: National Institute of Meteorology - INMET

Table 5. Actual and estimated yield in the AquaCrop model of the forage cactus cultivar *Opuntia stricta* (Haw.) Haw irrigated at frequencies of 7 and 28 days

Treatments (Frequencies of irrigation in days)	Yield	
	Observed (ton ha^{-1})	Estimated (ton ha^{-1})
I7	16.8837	16.6590
I28	14.3243	13.7720

Table 6. Difference between actual and estimated yield values of the forage cactus cultivar *Opuntia stricta* (Haw.) Haw irrigated every 7 and 28 days

Treatments (Frequencies of irrigation in days)	Yield Difference (ton ha^{-1})
I7	0.23
I28	0.55

Table 7. Validation of the AquaCrop model for irrigated forage cactus cultivar *Opuntia stricta* (Haw.) Haw

Statistics	Yield
RMSE	0.33
NRMSE (%)	2.11
PE	0.60
EF	0.89
D	0.98

RMSE - Root mean square error; NRMSE - Normalized root mean square error; PE - Prediction error; EF - Nash-Sutcliffe model efficiency coefficient; and d – Willmott's index of agreement

Agricultural techniques such as agrometeorological modeling used to estimate the productive potential of crops in different climate scenarios facilitate decision-making regarding the factors that affect production. Therefore, the parameterization was performed for forage cactus, since it does not exist in the AquaCrop software database. In the study, efficiency was measured through calibration and validation using statistical means. Based on the results presented, forage cactus proved to be agronomically viable in terms of production for the study region at irrigation frequencies of 7 and 28 days.

It is recommended that new studies be carried out to deepen the use of the Aquacrop model in this crop, which represents an alternative for the Semiarid region, as it is adapted to the climate, in addition to being an important forage resource for livestock in the region, having great acceptability by animals, high energy content, high concentration of water and minerals, high productivity per unit area, high phytomass production, in addition to being a thornless plant and resistant to the carmine cochineal, meeting the needs of herds and generating income for the producer (Santos et al., 2024).

Conclusions

1. The calibration and validation of the AquaCrop model for the forage cactus cultivar *Opuntia stricta* (Haw.) Haw, presented satisfactory results for the simulated yield when compared to the yield obtained in the field for the frequencies of 7 and 28 days, making AquaCrop a model applicable to the simulation of yield and responses to water stress of these crops, which can assist the producer in the decision-making process on his property.

2. The model's performance improves when there is greater water availability of the forage cactus cultivar *Opuntia stricta* (Haw.) Haw given that, as treatments receive less water, the difference between observed and estimated values increases.

Contribution of authors: J. R. Miranda contributed to research and methodology, data acquisition and analysis, and writing the original draft of the manuscript. D. A. Furtado contributed to the methodology and writing the manuscript. V. C. da Silva contributed to the methodology, data acquisition and writing the manuscript. A. G. de Oliveira contributed to writing the manuscript. V. P. R. Silva contributed to the methodology and writing the manuscript.

Supplementary documents: There are no supplementary sources.

Conflict of interest: The authors declare no conflict of interest.

Financing statement: There was no source of funding for the research.

Acknowledgments: The authors would like to thanks CNPq (National Council for Scientific and Technological Development) for supporting this study.

Literature Cited

Allen, R. G.; Pereira, L.; Raes, D.; Smith, M. Crop evapotranspiration: guidelines for computing crop water requirements. Rome: FAO. (FAO. Irrigation and Drainage Paper, 56), 1998.

Alvares, C. A.; Stape, J. L.; Sentelhas, P. C.; Gonçalves, J. L. M.; Sparovek, G. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, v.22, p.711–728, 2013. https://doi.org/10.1127/0941-2948/2013/0507

Alves, F. A. L.; Santos, D. C.; Silva, S. M. S.; Oliveira, M. A. B. Photosynthesis and gas exchanges of forage cactus varieties (*Opuntia and Nopalea*) grown under screen and irrigation. Pesquisa Agropecuária Pernambucana, v.25, p.1-15, 2020. https://doi.org/10.12661/pap.2020.004

Barrera Junior, W.; Morbidini, F.; Zammarchi, L.; Ghinassi, G.; Maucieri, C.; Borin, M.; Marta, A. D.; Verdi, L. Assessing the impacts of regulated deficit irrigation on soybean using AquaCrop. Revista Italiana de Agronomia, v.1, p.1-34, 2024. https://doi.org/10.1016/j.ijagro.2024.100023.

Bernardo, S. Manual de irrigação. 6 ed. Viçosa: UFV, 1995. 54p.

Bezerra, B. G.; Araújo, J. S.; Pereira, D. D.; Laurentino, G. Q.; Silva, L. L. D. Zoneamento agroclimático da palma forrageira (*Opuntia* sp.) para o estado da Paraíba. Revista Brasileira de Engenharia Agrícola e Ambiental, v.18, p.755-761, 2014. https://doi.org/10.1590/S1415-43662014000700013

Dantas, S. M.; Silva, V. P. R.; Silva, E. M. Calibration and validation of the FAO AquaCrop model for dryland and irrigated eggplant in a semi-arid climate region. Revista DELOS, v.17, p.01-20, 2024. https://doi.org/10.55905/rdelosv17.n61-011

Du, Y.; Fu, Q.; Ai, P.; Ma, Y.; Pan, Y. Modeling comprehensive deficit irrigation strategies for drip-irrigated cotton using AquaCrop. Agriculture, v.14, p.1-24, 2024. https://doi.org/10.3390/agriculture14081269

Edvan, R. L.; Fernandes, P. D.; Carneiro, M. S. S.; Neder, D. G.; Araújo, J. S.; Andrade, A. P.; Souto Filho, L. T. Acúmulo de biomassa e crescimento radicular da palma forrageira em diferentes épocas de colheita. Revista Acadêmica Ciências Agrárias e Ambiental, v.11, p.35-43, 2013. https://doi.org/10.7213/academico.011.004.AO04

Jiménez, K. Q.; Melo, T. M.; Louzada, J. A. Uso de dados de precipitação obtidos por sensoriamento remoto em um modelo agro-hidrológico. Irriga, v.306, p. 496-508, 2013. http://doi.org/10.15809/irriga.2013v18n3p496.

Leukel, J.; Zimpel, T.; Stumpe, C., Machine learning technology for early prediction of grain yield at the field scale: A systematic review. Computers and Electronics in Agriculture, v. 207, p.107721, 2023.

Miranda, J. R.; Furtado, D. A.; Silva, V. C.; Dantas Neto, J.; Souza, J. T. A.; Araújo, J. S. Physiology of the forage cactus cultivate *Opuntia stricta* (Haw.) Haw under different irrigation frequencies in the Semiarid. Revista Ceres, v.70, p.24-31, 2023

Raes, D.; Steduto, P.; Hsiao, T. C.; Fereres, E. AquaCrop the FAO crop model to simulate yield response to water. II. Main algorithms and software description. Agronomy Journal. v.101, p.438-447, 2009. https://doi.org/10.2134/agronj2008.0140s

Rosa, S. L. K.; Souza, J. L. M.; Tsukahara, R. Y. Performance of the AquaCrop model for the wheat crop in the subtropical zone in Southern Brazil. Pesquisa Agropecuária Brasileira, v.55, p.1-5, 2020. https://doi.org/10.1590/S1678-3921.

Sharafkhane, M. G.; Ziaei, A. N.; Naghedifar, S. M.; Akbari, A.; Verdi, A. Agricultural Water Management, v.306, p.1-14, 2024. https://doi.org/10.1016/j.agwat.2024.109153

Santos, M. R.; Oliveira, C. M.; Donato, S. L. R.; Fonseca, V. A.; Cotrim, C. E.; Batista, R. S. Palma forrageira irrigada com água salina sob densidades de plantio em três ciclos produtivos. Revista Nativa, v.12, p.542–550, 2024. https://doi.org/10.31413/nat.v12i3.16356

Silva, A. P.; Souza, P. A. Zoneamento agroclimatológico para produção da palma forrageira no semiárido. Brazilian Journal of Development, v.6, p.20048-20057, 2020. http://doi.org/10.34117/bjdv6n4-251

Soil Survey Staff. Keys to Soil Taxonomy. 13.ed. USDA - Natural Resources Conservation Service, 2022. 401p. Available at: https://www.nrcs.usda.gov/resources/guides-and-instructions/keys-to-soil-taxonomy. Accessed on: Jan 14, 2025.

Souza, D. C. F.; Lima, I. S.; Santana, J. A.; Almeida, A. Q.; Gonzaga, M. I. da S.; Santana, J. F. Zoneamento agroclimático da palma forrageira (*Opuntia* sp.) para o estado de Sergipe. Revista Brasileira de Agricultura Irrigada, v.12, p.2338-2347, 2018. https://doi.org/10.7127/rbai.v12n100715

Willmott, C. J. Some Comments on the Evaluation of Model Performance. Bulletin of the American Meteorological Society, v.63, p.1309-1313, 1982. http://doi.org/10.1175/1520-0477

Zhou, Z.; Plauborg, F.; Parsons, D.; Andersen, M. N. Potato canopy growth, yield and soil water dynamics under different irrigation systems. Agricultural Water Management, v.202, p.9-18, 2018. https://doi.org/10.1016/j.agwat.2018.02.009