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CROP PRODUCTION

Digital platform for experimental and technical support to the cultivation of cactus pear

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ABSTRACT. Among the forage species, especially in semiarid ecosystems, cactus pear is exceptional because of its high tolerance to adverse conditions and high productivity. Due to this alone, several studies have been conducted to identify the main technologies for this crop. Despite being consolidated and integrated, the cactus pear production system has limited accessibility, technical assistance, and availability of information for those dedicated to its production. This study aimed to present a digital platform, website, and applications to provide technical information on the cactus pear and demonstrate the efficiency of these applications through experimental data. On this digital platform, applications were made available for predicting the productivity of cactus pear using artificial neural networks (ANN) on a computer with routines in the R software and by simple linear regression (SLR) on smartphones on the Android system of the MIT App Inventor 2 platform. In addition, using the smartphone app, it is possible to obtain the cladode area through multiple linear regression (MLR). It is also possible to obtain the estimates of the experimental plot sizes by the maximum modified curvature, linear and quadratic methods with plateau response, relative information, comparison of variances, and convenient plot size. The platform provides technical information associated with the cactus pear crop from different sources (dissertations, theses, articles) and formats (video classes and teaching resources), offline for applications, and online with download for publications, dissertations, theses and articles, video classes, and several didactic resources. The biomathematical models integrated with the applications were highly precise in predicting the phenomena, in which the variation explained by the models in the prediction of responses for future observations had R^2 values of 0.95, 0.72, and 0.92, respectively, for productivity with computer-ANN and smartphone-SLR, and for the cladode area with a smartphone - MLR.

Keywords: digital agriculture 4.0; artificial intelligence; smartphone; online and offline models; *Opuntia* sp.

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Introduction

Among the forage species, the cactus pear is exceptional within the semiarid ecosystem because of its high tolerance to adverse conditions and high biomass production. Due to its importance for agriculture and livestock, several studies have been conducted on this crop, including on organic fertilization, planting densities and spacing (Fonseca et al., 2020; Lédo et al., 2020); photochemical efficiency of photosynthesis (Brito, Donato, Arantes, Donato, & Silva, 2018); soil chemical attributes (Padilha Júnior, Donato, Donato, & Silva, 2020), and mineral fertilization and planting spacing (Silva et al., 2016). Others highlight the use of cactus pear to feed heifers (Aguiar et al., 2015); rules for the interpretation of nutritional status (Alves, Donato, Donato, Silva, & Guimarães, 2019; Teixeira, Donato, Silva, & Donato, 2019); irrigation (Fonseca et al., 2019); different agroecossystems (Matos, Donato, Kondo, Lani, & Silva, 2021); production systems diagnostics (Jesus, Santos, Fernandes, Donato, & Silva, 2020); harvest prediction (Guimarães, Donato, Aspiazú, Azevedo, & Carvalho, 2019a); and experimental plot (Guimarães, Donato, Aspiazú, Azevedo, & Carvalho, 2019b).

Despite being consolidated and integrated, the cactus pear production system has limited accessibility, technical assistance, and availability of information to those dedicated to production in the semiarid region.

This occurs due to the barrier associated with technical-scientific language and connectivity obstacles, given that more than 71% of rural establishments in Brazil (3.64 million properties) still do not have access to the Internet (IBGE, 2017).

The digital platform www.cactuspearforrageira.com.br, therefore, seeks to provide extensionists, consultants, students, and rural producers with the technical knowledge of the production model developed for cactus pear with free, effective, and simple accessibility. On this platform, the information is conveyed through several sources, such as dissertations, theses, scientific articles, and video classes with the main researchers and cactus pear specialists in Brazil. Didactic tools are also available, associated with applications that make it possible to work without using the Internet on rural properties. There are also other resources that, when integrated, aid the decision making of the farmers, in addition to providing researchers with technical information for planning and conducting experiments, and students with the basis to maximize academic and professional performance (MAPA, 2018; Veimrober Júnior et al., 2019).

The use of information and communication technologies (ICT) has facilitated access to information and professional training, mainly because of the availability of digital platforms (Barbosa & Evangelista, 2017; Picoli, 2020). ICTs reconfigured the academic model for updating and mediating knowledge, allowing the expansion of borders and the overcoming of barriers, defined here as obstacles between the scientific and academic fields (Brito, Síveres, Mercado, & Neves Júnior, 2020) or even the rural producer. These technologies are vital and increasingly present both in academia and in the field (Ferraz & Pinto, 2017).

This technological revolution has reached numerous segments of the production process, including systems considered primary, such as agriculture (Massruhá & Leite, 2016). Technological advances in agricultural processes have improved automation, cost reduction, precision, and safety, especially with the use of mobile device applications, such as cell phones and tablets (Massruhá, Leite, & Moura, 2015).

Globalization refers to fair and sustainable economic development, in which technological advances enhance the strategic actions for the growth of Brazil and the world. ICTs have contributed to the expansion of multiple areas of knowledge, with effective, accurate, and high-magnitude responses to describe, solve, and outline highly complex unknowns. Through robust data processing systems, method automation, and information exchange, professionals and rural producers have been successful in several agricultural enterprises (Massruhá et al., 2015).

With the use of digital platforms, websites, and applications, we aim to obtain important results in an academic context, and significant advances with the adoption of productive techniques of the cactus pear. This platform can facilitate the popularization of science and technology. It is imperative to note that almost all Brazilian journals use the English language for their publications to deal with impact ratings, making it difficult for those who do not know a foreign language to access information, including producers, the main target audience.

This study aimed to present a digital platform, website, and applications to facilitate access to technical information about the cactus pear and to demonstrate the efficiency of these applications through experimental data.

Material and methods

The study was conducted at the State University of Montes Claros (UNIMONTES) in partnership with the Federal Institute of Bahia (IFBAIANO) between April and September 2020. In view of the composition, development, and consolidation of the cactus pear production system undertaken by the Federal Institute of Bahia, Campus Guanambi, Bahia State, Brazil and partner institutions, for over ten years (Aguiar et al., 2015; Silva et al., 2016; Donato, Donato, Silva, Pires, & Silva Junior, 2017; Brito et al., 2018; Alves et al., 2019; Guimarães et al., 2019a; Teixeira et al., 2019; Fonseca et al., 2019; 2020; Lédo et al., 2020; Guimarães et al., 2019b; Matos et al., 2021; Padilha Júnior et al., 2020; Donato, Borém, & Rodrigues, 2020), with the interdisciplinary research group - Agronomic Engineering and Information and Communication Technology, we sought to build a digital platform for robust, free and effective access to agronomic information concerning the crop.

The digital platform aims to allow dynamic and uninterrupted access to various sources and formats of information, such as dissertations, theses, and scientific articles. Other sources include video classes and teaching resources, as well as testimonies of experts and former students who developed studies of the cactus pear. The platform is routinely updated with the latest research.

In addition to this information, we linked to mobile applications the productivity prediction by artificial neural networks (ANN) and regression models (Guimarães et al., 2019a), respectively. Using the smartphone app, the area of the cladodes was determined using the multiple linear regression model (MLR) and the estimates of the experimental plot sizes by the methods of modified maximum curvature, linear and quadratic with plateau response, relative information, comparison of variances, and convenient plot size (Guimarães et al., 2019b).

Site

The Internet portal about the cactus pear cv. Gigante was developed with Wordpress software to enable digital access to useful information about the crop. This technological tool enabled the creation of the website www.palmaforrageira.com.br, in which, through an open interface, the contents related to the crop were grouped according to their similarities. Thus, within the concept of taxonomy, partitioned accesses to different information formats were considered, such as VIDEOCLASSES - with the various themes on the cactus pear production system; APPLICATIONS - to access information on the crop; EVENTS - consisting of seminars, field days, workshops, and lectures; PUBLICATIONS - various materials combined in dissertations, theses, scientific articles, books, and agricultural reports, among others; TEACHING RESOURCES - theoretical and practical classes, representations of digital and *in vivo* models (Figure 1).

Figure 1. Digital platform to access technical information about the cactus pear crop. Source: Prepared by the author. View site demo: https://youtu.be/iO8pOKGUsW4.

The configuration of the website made it possible to quickly access the files available on the page, with the option of downloading different materials and academic reports. With this, the digital platform has an excellent structure, with didactic principles and dynamic and interactive visual that adapts to any computer screen and, or, smartphone. This contributed to wide use by students, professionals, and producers (Figure 1).

Application for smartphones and tablets

For application development, we chose open-source technologies that offer good performance, a good interface, and communicability, with access to some information even without an Internet connection. With a focus on technology and innovation, the digital model provides the producers with essential information on the productivity of the cactus pear, in addition to developments related to animal feed. Still, the digital model gathers specific information on size and format estimates of experimental plots for phenotypic evaluation with cactus pear as a subsidy to the researcher in the field experimentation with the required accuracy.

We used the QUASAR Framework tool to build the PalmaForrageira application to facilitate and integrate various web technologies. The JavaScript programming language, which provides a better interaction between the system's functionalities and the HTML markup and CSS styling language, allowed the creation of the basic visual structure of the application. To store data on the device itself, we used LocalForage, a JavaScript library that provides a basis for data storage. Throughout the development, the usability of the system was considered to contemplate the most appropriate way to make resources and functions available on the application screen, prioritizing some characteristics such as common language, illustrations, and self-help.

Then, the QUASAR Framework was used to develop the functionalities of the application by integrating information from the IF BAIANO Cactus Pear Production System (Donato et al., 2020). In the next step, we carried out tests of the application, which allowed the identification of possible flaws in coding, layout, and available functionalities. The application was published and made available through the digital platform www.palmaforrageira.com.br (Figure 2).

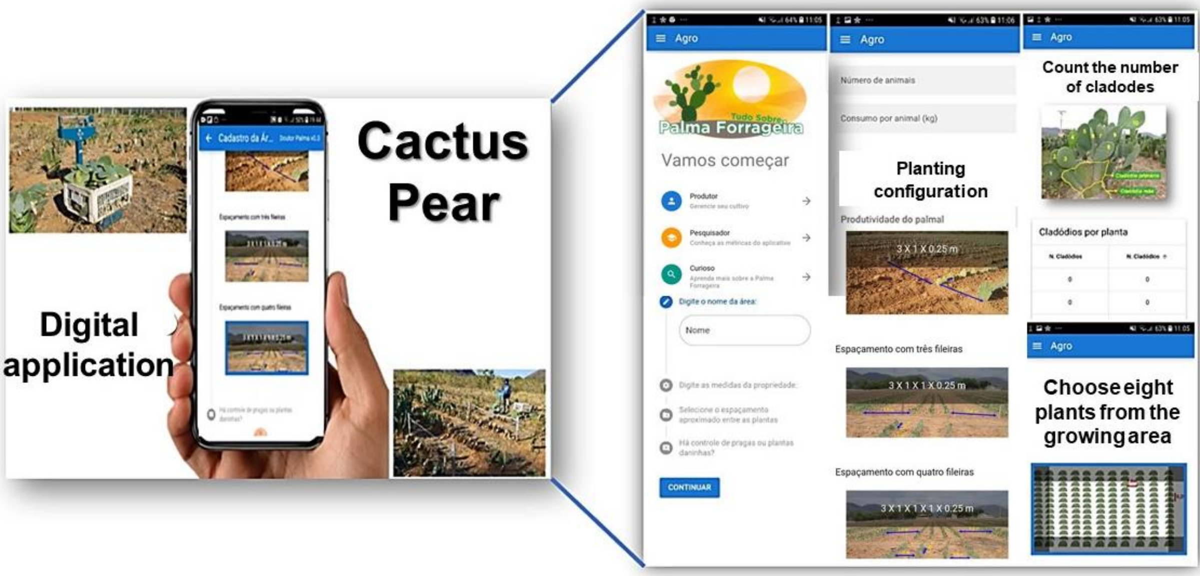

Figure 2. Illustrative demonstration of the application on the cactus pear. Source: Prepared by the author. See application presentation: https://youtu.be/nCDfFhA-oX0.

Computer application by R software

The integration between the website www.palmaforrageira.com.br and the R software (R Development Core Team, 2018), available on the Internet http://cran-r.c3sl.ufpr.br/bin/windows/base/R-3.3.1-win.exe, optimizes and ensures access to information, as digital platforms are not only robust but also free.

The cactus pear application for the computer was written in R software using the shiny package (https://shiny.rstudio.com/). R software enables an interactive language for numerical calculation, data management, and graphical presentation. The source code of the application is available at https://github.com/samuelmacedo83/Cactus pearForrageira and can be accessed through the R program or with the standalone version (PalmaForrageira.rar). Developed by Ross Ihaka and Robert Gentleman in New Zealand, R software provides a variety of information built in the form of routines with researchers around the world.

The application consisted of several screens with agronomic information, among which were the estimates of productivity using simple linear regression (Figure 3a) and using ANN (Figure 3b).

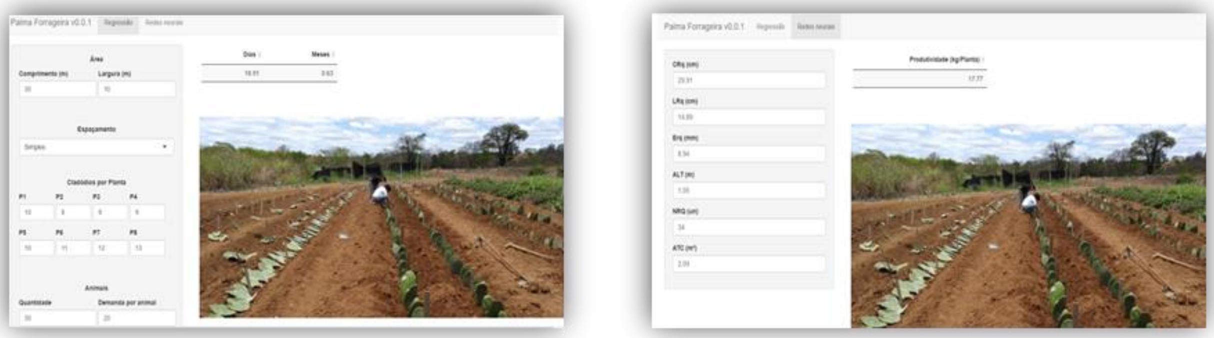

Figure 3. Productivity prediction by SLR (a) and by ANN (b).

For regression estimation, four parts were necessary: definition of the cultivated area, spacing between plants, productivity of the cactus pear, and dimensioning of the number of animals to be fed, according to the script model. Using ANNs, the estimate was drawn from a pre-trained model that was added to the application, with no further training of the model being necessary. The application was also submitted as an R package to the CRAN with English and Portuguese versions.

With this digital platform, we sought to integrate techniques, technologies, and high-efficiency performances to ensure the automation of agricultural processes with cactus pear through mobile devices such as smartphones and computers. This integrated digital platform allows for adequate rural planning with more productive security, cost reduction, and production predictability.

Application validation

To validate the predictive models associated with mobile applications - smartphone and computer, we used an experimental area with the cactus pear 'Gigante' (*Opuntia ficus-indica* Mill), in the second production cycle, planted at a spacing of 1.5 m between rows and 0, 15 m between plants, with 3,042 m². We randomly selected 13 evaluation plots in the area, with eight basic units (BUs) per plot, totaling 104 plants, each of which was identified as a UB (Figure 4), according to the statistical determination proposed by Guimarães et al. (2019b).

Figure 4. Useful portion for validating predictive models integrated with mobile applications - smartphone and computer.

In each plot, the morphological characteristics of plant height (m) and length and width of the cladodes (cm) were determined using a measuring tape, the thickness of the cladodes (mm), using a digital caliper; number of cladodes, by direct field count, and areas of the cladodes (cm²), using the digital image technique, in which the digital images were segmented, identified, and measured in each cladode defined using a specific routine with the EBImage package in the R software (R Development Core Team, 2018). The guidelines regarding the color palettes and computational algorithms used are available on an online platform (https://github.com/AlcineiAzevedo/AreaCladodioCactus pear). The total area of the cladodes (m²) was obtained by multiplying the areas of the cladodes of each plant by factor 2. The total mass of the cladodes was obtained using an analog field scale, and the results are expressed in kg.

After determining the morphological and yield characteristics, productivity was estimated using mobile smartphone apps (SLR) with the predictive variable number of cladodes and the ANN model for the computer with the variables plant height, length, width, thickness, total area, and the number of cladodes. The area of the cladode was estimated using the width and length of the cladodes (MLR). Actual and estimated productivity (SLR and ANN) were compared graphically to attest to the predictive safety of the models, and the same procedure was performed with the variable area of the cladodes (MLR).

To confirm the predictive safety of the SLR, ANN, and MLR models, the determination coefficient (R^2), adjusted determination coefficient (R^2_{adj}), mean square error (EQM), Akaike (Akaike), and Bayesian (BIC) information criteria, and the selection criteria defined by the log-likelihood, which represents the value of the log-likelihood function considering the parameter estimates.

Description of application screens

Screen 1 or the application presentation gathers general information for the user, such as the tab for registering personal data and opening the account in the digital system. Screen 2 offers access to the digital platform www.palmaforrageira.com.br. Screen 3 is linked to the productivity prediction models (smartphone-SLR and computer-ANN) and the estimate of the cladode area for both mobile resources. Screen 4 establishes the metrics with different models for estimating the size of the experimental plot (Figure 5). To test the efficiency of the applications, productivity prediction, and proof of this productivity were conducted in several experimental units cultivated with the cactus pear.

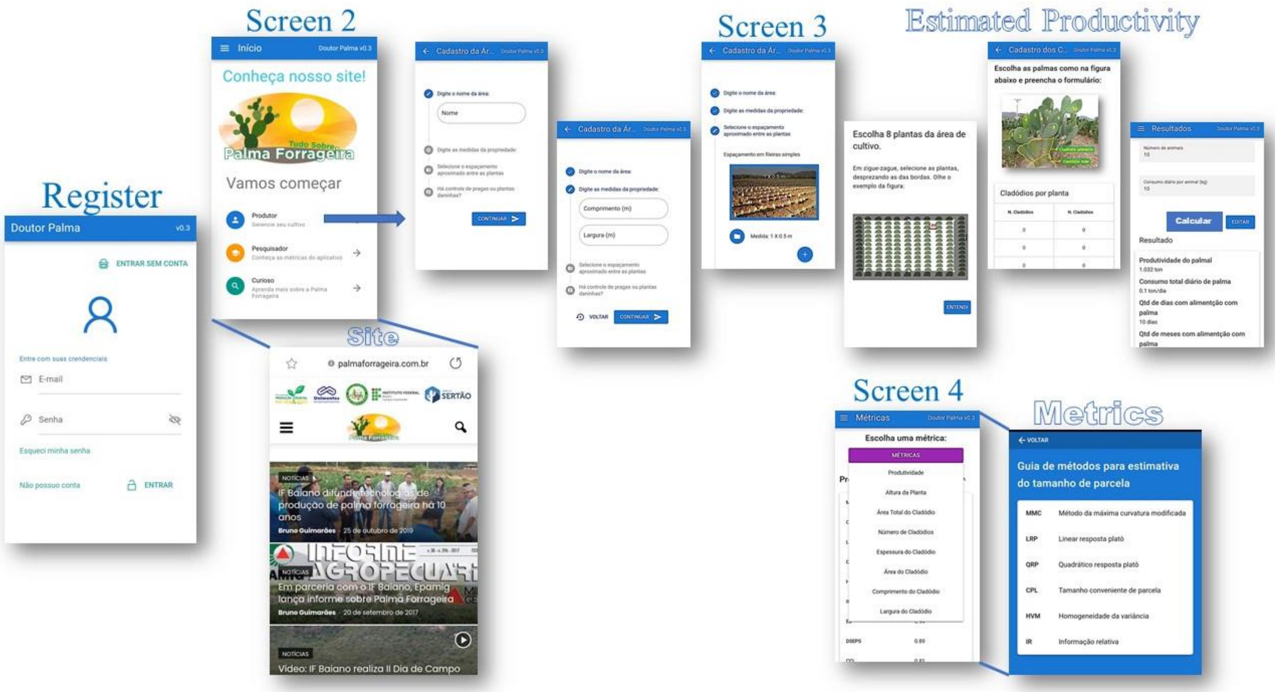

Figure 5. Description of the applications’ screens.

Results and discussion

The descriptive statistics of the morphological characters corresponding to the area for application validation are shown in Table 1, with the greatest stability for the width and length of the cladodes. The lowest and highest values of the variation coefficients were associated with the width and mass of the cladodes, respectively. As for the correlation with productivity, the highest values were linked to the total area of the cladodes, followed by the number of cladodes, plant height, area, length, width, and thickness of the cladodes (Table 1). This information, in addition to enabling the characterization of agronomic variables, highlights the variables with the greatest potential in predicting productivity (Guimarães et al., 2019a) and the estimate of the cladode area (Lucena, Leite, Simões, Simões, & Almeida, 2018a).

We tested the biomathematical models for predicting the productivity of cactus pear using the PalmaForrageira package in the R software with ANN and an application compatible with the Android system for smartphones and tablets, using simple linear regression (SLR). The practical applicability of these models showed high efficiency in predicting responses for future observations, with adjustments expressed by the coefficient of determination (R^2) of 0.72, and 0.95, in that order, for SLR and ANN (Figure 6).

In a practical context, the use of the SLR and ANN models represents higher applicability in the field for the former to the detriment of the latter. This was expected because simple linear regression uses a single predictor variable that, because it is easily obtained in the field and has a satisfactory R^2 value, makes the model feasible. The opposite occurs with ANNs, which employ more regressive functions and, according to the adjustment made in this model, require a higher number of independent variables to compose the prediction, which makes applicability difficult. However, the ANN model ensures a predictive quality superior to that of the SLR, which is also more intuitive, as it contains a higher number of predictive variables (Figure 6).

Table 1. Descriptive statistics and correlation of vegetative characters total cladode area (TCA - cm²), plant height (PH - m), number of cladodes (NC - unit), cladode area (CA - cm²), cladodium length (CL - cm), cladode width (CW - cm), cladode thickness (CT - mm) and mass of the cladodes (MC - kg) in 'Gigante' cactus pear.

	TCA	PH	NC	CA	CL	CW	CT	MC
Minimum	2510.22	52.00	4.00	8.00	22.94	12.31	13.74	2.88
Means	8122.91	85.80	11.42	343.82	28.76	15.43	24.50	8.81
Median	7796.89	85.00	11.00	347.53	28.95	15.57	24.65	7.96
Maximus	22916.98	130.00	28.00	490.65	34.14	18.25	31.02	26.73
DP	3767.67	17.189	4.57	68.29	2.65	1.417	3.28	4.49
CV%	46.38	20.03	40.05	19.86	9.21	9.18	13.38	50.96
Correlations								
TCA	1							
PH	0.74	1						
NC	0.92	0.69	1					
CA	0.46	0.52	0.24	1				
CL	0.46	0.53	0.23	0.81	1			
CW	0.45	0.47	0.22	0.77	0.77	1		
CT	0.14	0.03	0.082	0.19	0.15	0.20	1	
MC	0.97	0.71	0.88	0.50	0.50	0.50	0.334	1

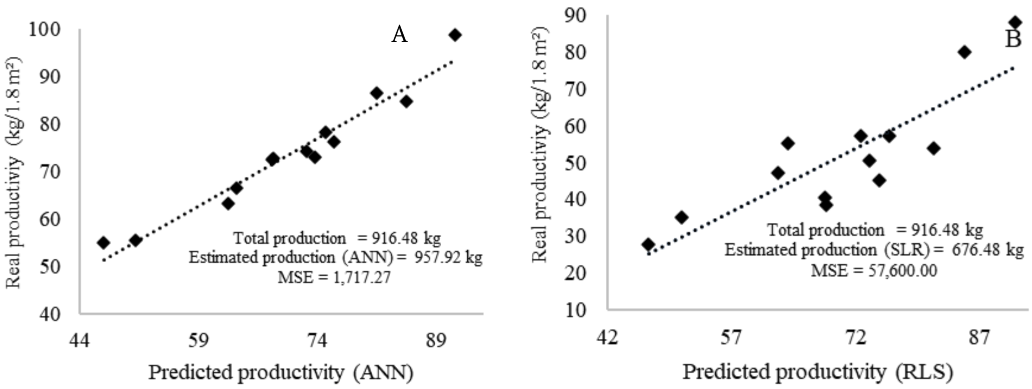

Figure 6. Validation of predictive models in mobile applications for computer (ANN) (A) and smartphone (SLR) (B) compared to actual productivity in 'Gigante' cactus pear. *** Significant at $p \leq 0.001$ by t test.

Searching for the best mathematical adjustments for the prediction of agricultural phenomena, Michelon, Taconeli, Vieira, and Panobianco (2019) evaluated classes of GLM (generalized linear models) to determine the seed count of *Eucalyptus cloeziana*, indicating that the Poisson distribution is the most adequate for the seed count data for this species. Normally, more complex models ensure higher prediction assertiveness; however, it is worth considering the practical applicability of the model, especially with the use of simple and easy-to-use tools.

The integration of these devices into the production system is associated with the definition of the Internet of Things, in which computational resources through analysis, sensors, and techniques generate highly efficient information to ensure decision making with greater assertiveness (Monostori, 2014) and foster strategic rural planning. However, Internet connectivity can be a limiting factor in regions that lack this service, so it is recommended that the digital tool is robust, free, accessible, and allows access to information even in offline mode.

In this context, the cactus pear application can function offline but with frequent system updates. As new information is generated, the producer/technician registers the area for cultivation and inserts the technical information about the cultivated cactus pear, such as the dimensions of the area, spacing between plants, number of animals to be fed, and other information corresponding to the ANN, SLR, and MLR models. Then, specific recommendations will be obtained, such as productivity and the number of animals to be fed during the dry season (Figures 1 and 5). The basis of the information system is compiled in the work of Donato et al. (2020) and several publications, as previously mentioned.

Regarding the prediction models, it is worth considering that the varietal performance, the productive performance, and the adaptability of the cactus pear are strongly associated with the cladode area (Pinheiro et al., 2014). In addition to being the photosynthetically active surface of the plant (Lucena et al., 2018a), the cladode area is fundamental for determining biomass production, transpiration intensity, cladode area rate, specific cladode area, and the cladode area index (Schmildt, Amaral, Schmildt, & Santos, 2014).

For this reason, knowledge about the area of the cladode is very important, especially because it presents morphological irregularities frequently linked to the presence of thorns, which makes it difficult to work in the field (Lucena, Leite, Cruz, & Sá, 2018b). Thus, in search of higher precision associated with practical applicability for obtaining the cladode area in an indirect and non-destructive way, we linked to mobile applications, such as smartphones and computers, the model for estimating the cladode area through the dimensions of length and width, as shown in Figure 7.

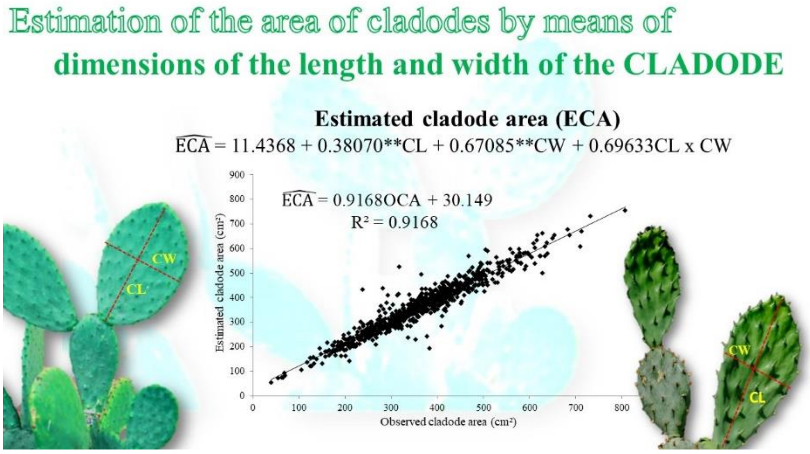

Figure 7. Digital resources linked to mobile applications to estimate the cladode area using the dimensions of the length (CL) and width of the cladode (CW).

To verify whether the models suggested in this study met the assumptions of statistical analyses, indicators of the quality of Akaike (AIC) (Akaike), Bayesian (BIC), and log-likelihood adjustments were considered. In this way, the SLR and ANN models were selected based on these parameters to integrate mobile applications with use on smartphones and computers, respectively, to ensure application users maximum predictive efficiency with the 'Gigante' cactus pear. In addition, the mean square errors (MSE) associated with the SLR and ANN models were determined. There was greater assertiveness for the ANN model, with MSE = 138.93, compared to SLR, with MSE = 4500.83. To test the quality of the model as a function of the area of the cladode (AC), we considered the MSE and R^2 for both the training and validation samples (Table 2). The models selected to compose the applications were also based on studies by Guimarães et al. (2019a).

Table 2. Parameters of the productivity prediction models using Akaike (AIC) (Akaike), Bayesian (BIC) and Mean Square Error (MSE) information criteria.

	AIC	BIC	log-likelihood	MSE
ANN	68.77	70.47	-31.39	138.93
SLR	90.90	92.59	-42.45	4500.83

Variables	Method	Training		Validation	
		MSE	R^2	MSE	R^2
AC	MLR	0.00165	0.924	0.00156	0.925
	ANN	0.0353	0.905	0.00207	0.903

In addition to the productivity prediction models (SLR and ANN) and the cladode area (MLR), the mobile application developed on the MIT App Inventor 2 platform offers statistical metrics to support the researcher regarding the models for determining the optimal size of the experimental plot, according to the studies developed by Guimarães et al. (2019b). In this sense, the application has a screen related to the research, in which it is possible to select several experimental plots according to the objective, the characteristics to be evaluated, and/or the precision required by the study. The selection criteria were based on the smallest experimental area, reflecting the maximum efficiency of use of the experimental area (EUEA). Cactus pear researchers can find relevant and applicable information for decision making regarding experimental planning with precision and agronomic characteristics to be investigated or the methods used.

On a platform similar to the present study, integrated with the R software, Cruz (2016) built the Genes application for the analysis and processing of phenotypic and molecular data using different biometric models. The model generated met the principles of connectivity and the integration of high-efficiency techniques to allow parameter estimates to understand biological phenomena essential to decision making with different levels of prediction and genetic selection. Still, as an instrument of inclusion, it is worth noting that the platform proposed in this study also ensures offline service to the user, which favors access to information even without Internet connectivity. As a result, subsidies for genetic studies applied to plant and animal breeding programs are already a reality and have enabled scientific development through digital integration (Cruz, 2013; 2016).

The construction of dynamic systems that promote major changes in resolutive production models with the use of technologies to access packages, services, and data processing information and information systems can maximize monitoring and predictive security in the field (Monostori, 2014). Likewise, technological innovation has increased in the scientific field, and its participation in teaching, research, and extension platforms is already a reality. Thus, the knowledge conveyed in digital format favors access, update, and expansion of existing information (Massruhá et al., 2015). In addition to timely disseminating new research, the digital platform with cactus pear is a robust and free knowledge source for farmers.

The digital platform www.palmaforrageira.com.br brings together the main lines of knowledge about the culture under study, with different sources and formats, as already described. The promotion of channels on the Internet as information or user support tools is not exclusive to this study, whereas other researchers have already used websites (http://www.ufv.br/dbg/genes/genes.htm, http://www.ufv.br/dbg/biodata.htm, and http://www.livraria.ufv.br/) and social networks (www.facebook.com/GenesNews) to facilitate digital access to information (Cruz, 2016).

Technological resources have significantly changed several educational (Brito et al., 2020) and agricultural (Massruhá et al., 2015) sectors, resulting in a networked society with strategic means for effective access to academic tools along with the effective participation of professionals. In this context, many factors are interrelated, such as education, science, and the field; the use of technological tools seeks to integrate and bring these segments together. Thus, it expands the repertoire of possibilities in the search for information and, most importantly, the construction of collective, connected, and dynamic knowledge (Massruhá & Leite, 2016), characterized by continuous evolution.

The digital platform thus allows the transposition of knowledge from complex scientific articles to easily understandable information. Furthermore, the popularization of science and the transfer of technology are imperative for end-users of agricultural technologies, including researchers, extension workers, agricultural science students, or rural producers.

Conclusion

The digital platform for agronomic representation of cactus pear proposes to support, with singular efficiency, extension workers, researchers, consultants, and technicians in general, as well as students and rural producers. Digital resources with easy access to the user (online and offline) offer simple and effective technical information for the dimensioning of cultivation areas, management recommendations according to the crop development stage, productivity prediction according to the number of animals to be fed, estimate of the area of the cladodes, determining the size of the experimental area, and other subsidies. The biomathematical models integrated with the mobile applications showed high precision for the prediction of the phenomena; the variations explained by the models in predicting responses for future observations showed R^2 values of 0.95, 0.72, and 0.92, respectively, for productivity with computer-ANN, smartphone-SLR, and smartphone – MLR, for the cladode area.

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