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ORIGINAL RESEARCH ARTICLE

Intelligent fertigation, pillar of sustainable agriculture

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ABSTRACT

The growing demand for food in the country has required an increase in agricultural production levels and, with it, an increase in irrigation systems. Among the most widespread are central pivot irrigation systems, but their large number and variety make their optimal configuration difficult, generating overexploitation of natural resources such as water and threatening the sustainability of agriculture and the country. For this reason, the objective of this research was to implement software that would allow obtaining the appropriate configuration of this equipment using information on the type of crop, the agro-climatic conditions of the region, and the soil in order to obtain maximum utilization. As a result, an application capable of performing the calculations so that the value of water delivered by the system is closer to the estimated needs for a crop in each of its phases was achieved. To demonstrate this, an experimental study was carried out in field conditions in the agricultural enterprise La Cuba in Ciego de Avila; it showed that, with the use of the software, there was a saving of up to 94.5% of the water previously misused. In addition, the level of liquid provided allows the sowing to be in better conditions to reach its optimum yield. As an added value, the software has a minimalist and intuitive interface, which allows real-time visualization of field information.
Keywords: sustainable agriculture; configuration and control software; irrigation; center pivot machines

1. Introduction

Meeting the country's, and the world's, growing demand for food is a challenge that entails enormous economic and environmental costs. Due to its negative impacts on natural resources and the environment[1], the current trajectory of increasing agricultural production is unsustainable; in fact, there is a clear correlation between growth in agriculture and its impact on natural resources[2]. Some of the consequences of this relationship are evident in the fact that, for example, up to 75% of crop genetic diversity has been lost, and one third of agricultural land was already degraded at the beginning of this century[1]; this proportion is possibly even higher today.

The global challenges we face are the rapid degradation of natural resources and increasing scarcity, at a time when demand for food, feed, fiber, and goods and services from agriculture is growing rapidly[2]. It is well known that agriculture has been a victim of global climate change in recent years and, in turn, one of the

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main contributors to it.

When it comes to high levels of production, it is very difficult to think of the development of organic agriculture without the use of genetically modified organisms or synthetic chemicals. However, it is necessary to make optimal use of natural resources, especially water, in order to obtain sufficient food while respecting the environment and preserving the fertility of the soil. In the case of Cuba, at the end of the 80's of the last century, a decrease in productivity began to be observed, related to the deterioration of soils mainly due to agricultural practices that relied on the so-called technological packages, which marked the beginning of a new vision that tried to promote intensive technologies based on a better use of natural resources. In this sense, conditions were even created for the national production of sprinkler irrigation elements in factories such as "José L. Tassende" in Manzanillo and "Vasil Levski" in Cienfuegos[3].

From this moment on, the use of different mechanized irrigation systems began. The center pivot systems were the most successful due to their characteristics and advantages and, therefore, the most widespread until today. However, given the number of factors and variables involved in the efficient application of water using pivot-type equipment, even for relatively small plots of land, and the fact that the needs of each crop vary constantly, it is very difficult to make the appropriate calculations for each case using traditional methods. That is why it is a problem at present that, in Cuba, there is no tool to quickly and reliably configure the central pivot irrigation equipment in order to achieve the necessary adaptability to changing agro-climatic conditions and to obtain the maximum use of them. The objective of this research is to provide a solution to this problem using computer technologies. For this purpose, it is presented software that allows obtaining the best configuration for center pivot irrigation equipment, taking into account information on the type of crop, soil characteristics, and agroclimatic conditions of the region. This system was used as an experiment in the agro-industrial enterprises of Ceballos and La Cuba in the province of Ciego de Avila.

This article is structured as follows: a brief analysis of the current situation of irrigation calculation systems. Then, the proposed irrigation equipment calculation and control system are presented. Subsequently, an evaluation of the impact of the proposed system on agricultural entities in Ciego de Avila is made. Finally, the conclusions of the research are presented.

2. Materials and methods

Initially, the lands currently occupied by the provinces of Artemisa, Mayabeque, and Matanzas had the bulk of the central pivot machines installed in the country, coinciding, in addition, with the fact that they were the provinces with the greatest contribution to agricultural production per unit of sown area, which demonstrated the feasibility of these systems and motivated their expansion to the rest of the national territory. From then on, depending on the economic conditions and the political situations that had to be overcome, different machines of this type were acquired. Most of the machines obtained by Cuba belong to the firms OTECH, RDK, Western, and Fabre; configuring them to obtain optimum results is neither trivial nor generic since each one has different specifications in automation and control technologies. The intrinsic difficulties of this process are also established because, in addition to the technical particularities of each technology, there are other conditioning elements such as the characteristics of the type of soil, the requirements of the crop in each of its cycles, and the agro-climatic conditions of the planting area.

Once the amount of water required has been established according to the stage of the crop and the soil conditions, it is necessary to resort to the technical parameters by which the irrigation machine is governed. These can be: the speed of the last tower; the estimated time per revolution; and the timer setting, which establishes the flow of water to be applied per unit of area covered. Currently, in all cases, the settings are made based on approximations to the values provided by the manufacturer, which means that thousands of cubic meters of water are wasted, or not applied, in each crop cycle, thus wasting the liquid and affecting yield, as explained below.

At the end of the 1970s, the FAO (Food and Agriculture Organization of the United Nations) found Equation (1), which describes the correspondence between the yield of a sowing and its evapotranspiration values[4]:

$$(1 - \frac{Y_r}{Y_m} = K_y(1 - \frac{ET_r}{ET_m}) \quad (1)$$

where, Y_m and Y_r are the maximum and actual yields, ET_m and ET_r are the maximum and actual evapotranspiration, respectively. The yield response factor (K_y) establishes the relationship between final production and water use in a crop, its values are crop specific and vary for each plant cycle. This equation can be plotted in a general way, since the exact values are specific to each plant, as shown in **Figure 1**.

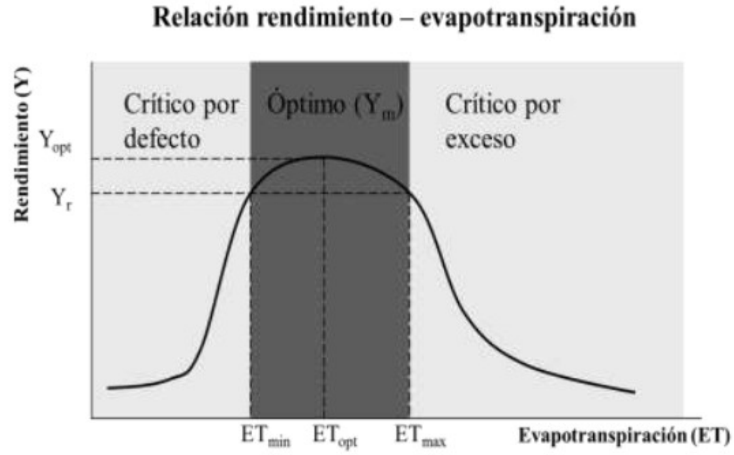

Figure 1. Relationship between evaporation and crop yield.
Yield - evapotranspiration ratio, Yield (Y), Critical by default, Optimum (Y_m), Excessive criticism, Evapotranspiration (ET).

It represents the critical points for under- or over-application of water and the optimal application window.

As can be seen on the abscissa axis, near-maximum crop yields can be found within a given range of evapotranspiration values. However, the productivity of the plantation is markedly lower than could be expected when the water provided is such that the evapotranspiration of the system is lower or higher than the established limits. For this reason, it can be stated that, especially in the climate of the country, although crops are generally more sensitive to water deficits, their productivity is also affected to a greater or lesser extent, depending on the plant, by excess moisture. Hence, a rounding in the configuration of parameters in center pivot machines that implies a water delivery different from that required by the crop does not guarantee optimum production and generally implies unnecessary consumption.

Nowadays, there are numerous applications aimed at optimizing the resources used in crops. These systems also provide recommendations on fertilizer types, doses, and application based on soil, water, and foliar analyses and the nutritional requirements of the crop. Among the most representative are: eFoodPrint[5], FertiSoft Cultivos[6], Ocean Business Interactive Platform[7], Orcelis Fitocontrol[8], and Smart Fertilizer[9]. However, its practical use in Cuba is limited by:

If it is decided to use their recommendations regarding fertilizers, the products they suggest in their plans are often not available, for price or other reasons, in Cuba.

They do not adapt to the heterogeneity of the irrigation and cultivation systems installed.

High acquisition, deployment, set-up, and support costs.

For these reasons, the creation of a system that is adapted to the conditions of our country is justified, which must comply with a minimalist, intuitive, and attractive interface as an added value of vital importance since it must be operated mainly by the personnel directly linked to the productive tasks in the field.

3. Proposed system

For the development of the system, a combination of agile methodologies was used: Scrum for project management[10]; and XP for development[11], employing Test Driven Development (TDD)[12]. This combination of methodologies is not new; it has already been widely employed without violating the principles of either[13].

It was decided that the application would be web-based. Python language was used for its implementation, mainly because it is very flexible; its code is readable and well organized, which facilitates maintenance and further development; it also allows the use of C and C++ libraries, which can be used to offer complex functionalities for which the creation of a library from scratch could be very costly. Web2Py was used as a development framework, among other reasons, because it offers a very organized structure and syntax; additionally, no security incidents have been reported to date in any site developed with it[14].

As a consequence of the use of this development framework, the Model-View-Controller (MVC) architectural pattern was used. Following this philosophy, the representation of the data (model), the presentation of the data (view), and the implementation of the functionalities (controller) were separated. This distribution can be observed in **Figure 2**, where the most relevant elements are shown and the rest follow the same pattern.

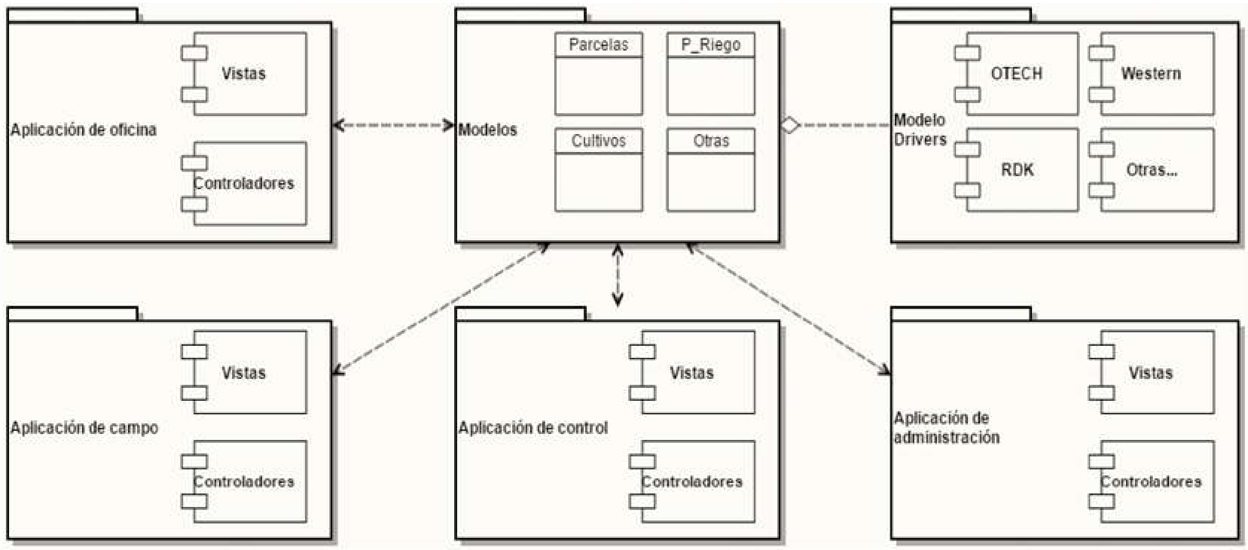

Figure 2. Diagram of application component packages.

Figure 2 shows the logical distribution of the software components of the proposed system, which is composed of six fundamental packages: office application, which contains the irrigation and planting plans, the specifications of soil types, crops and irrigation machinery; field application, in charge of representing the necessary information for the field operator using augmented reality techniques; control application, establishes the necessary configurations to make irrigation plans effective by automated systems; system administration, manages the security and integrity of the information; models, contains the databases related to the information necessary to carry out the sowing and cultivation plans; drivers, guarantees the adaptability of the application to the high heterogeneity of the irrigation and cultivation systems installed in Cuba.

Once the application is deployed, it can be accessed using an authentication mechanism based on a username and password. A role-based mechanism was used for authorization, whereby each authorized user must belong to one or more of the roles defined below:

Soil Manager: Updates the composition data of soil types and plots; your modifications to the system must be supported by laboratory tests or reliable bibliography.

Irrigation equipment manager: manages the technical data of the available irrigation machinery; its modifications must be supported by the original catalogs.

Crop manager: manages plant data; its modifications must be supported by reliable bibliography, preferably issued by the Ministry of Agriculture.

Agronomist: can make irrigation and planting plans. In addition, he can review the historical records of the plot and make modifications to the requirements established for the crop.

System Administrator: Only has access to assign users to roles.

Once the system was completed, in order to analyze its impact, an experimental study was carried out in 2016 at the agricultural enterprise La Cuba in the province of Ciego de Avila. The cultivation of black beans was done in ferrallitic rejo soil without considering rainfall and using a machine with the following characteristics:

Electric Central Pivot Irrigation Machine: OTECH with 5 Towers.

Flow rate: 164 m^3 /h.

Total length: 333.6 m.

Area: 34.96 ha.

Table 1 shows the specifications for the irrigation machine used, taking as an independent variable the amount of water to be applied in millimeters and the configuration necessary to achieve it in percentages of the timer. It is important to note that these values are provided by the manufacturer and are those currently used by approximation in hand planning. Although this equipment, like most of those available in Cuba, allows the chronometer to be set to more accurate values, it is necessary to have automatic systems and, above all, a quick response mechanism capable of providing the necessary values without having to calculate them every time a determining factor changes.

Table 1. OTECH 5-tower center pivot irrigation machine specifications.

Application（mm）	Config. （%）	Application（mm）	Config. （%）
5.72		16.34	
6.35		19.06	
7.15		22.88	
8.17		28.59	
8.80		38.13	
9.53		47.66	
10.40		63.54	
11.44		95.32	
12.71	45	190.63	
14.30			

Application - Application of water sheet (millimeters). Config. - Timer configuration (in percent).

As can be seen, the use of the table provided by the manufacturer does not allow a precise supply of the amount of liquid required by the crop. If the values corresponding to the lowest configuration percentages are taken, significant differences can be observed, which, as a consequence, make it impossible to think of the correct contribution of a previously calculated exact value.

Experimentally, this situation was evidenced during the study when, using the traditional calculation method, an agronomic design was made for the target crop, the results of which are shown in **Table 2**. The results are shown in **Table 2**. In this table are specified the water needs for each phase of the crop, the regulation used in the timer of the irrigation machine, the actual amount of water delivered by the equipment in the chosen configuration, the days after which irrigation should be applied again during the cycle because the water, due to evapotranspiration, has decreased its level in the soil until reaching the productive limit, as well as the difference between the water actually applied and the calculated needs.

Table 2. Manual agronomic design used for bean cultivation.

CC (days)	ARH (m^3 /ha)	ARV (m^3 /turn)	IR (days)	RM (%)	AEH (m^3 /ha)	AEV (m^3 /turn)	Difference (m^3 /turn)	(m^3 /crop cycle)	%
-	365	12,760.4			381.3	13,330.248	569.8	-	
0–30	183	6397.68			190.6	6663.376	265.7	2657.0	104.2%
31–60	244	8530.24			228.8	7998.848	–531.4	–3985.4	93.8%
61–90		9439.2			289.9	10,134.904	695.7	5217.8	107.4%
91–120	242	8460.32			228.8	7998.848	–461.5	–3461.0	94.5%

CC- Crop cycle. ARH - Water required per hectare. ARV - Water required per turn. IR - Irrigation interval. RM - Regulation of the machine used. AEH - Water delivered per hectare. AEV - Water delivered per turn.

It can be observed that there are differences, both for excess and deficit, in the amounts of water used in each cycle with respect to the needs of the crop. For example, during the cycle from days 31 to 60 of the crop, 3985.4 cubic meters of water were not applied, that is, 6.2% of the water required by the plant was missing; however, in the following cycle, between days 61 and 90, 5217.8 cubic meters of water were used unnecessarily, which means that 7.4% of the necessary liquid was wasted.

4. Results and discussion

As previously stated, a computer system was proposed; it is intended to work in two different ways: as a software without dependencies; or as a module of a precision agriculture system. In the first case, no prior installation or configuration is required; in the second, a more complex deployment is necessary, which is foreseen following the scheme shown in **Figure 3**.

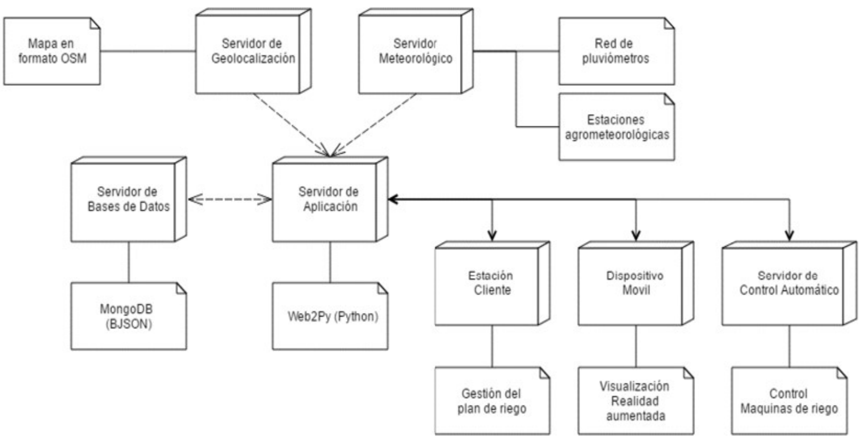

Figure 3. Deployment diagram of the system as a module of a precision agriculture system.

Figure 3 shows all the components that are part of the deployment of the application within a precision agriculture system, where they intervene:

Weather server: responsible for providing information on current weather conditions and forecasts for the region. These come from agro-meteorological stations in the territory, as well as the provincial rain gauge network.

Database server: contains all the crop information necessary for irrigation plans. Among them are the technical instructions for each crop, the personnel available for contracting, as well as the yield history of the plots, among others.

Geolocation server: allows the organization, storage, manipulation, analysis, and modeling of geospatial information about the region where the crops are located.

Application server: contains the application for the calculation of the necessary configurations to make the irrigation schedules effective. This is the main core of the proposed system.

Client station: ensures the management of irrigation schedules and information related to plots, crops, and irrigation equipment on the client side.

Mobile devices feature a minimalist, intuitive, and attractive interface. It allows real-time visualization of field information using augmented reality techniques.

Automatic control server: it is in charge of executing in real time the irrigation schedules generated by the application server for each specific irrigation system.

In a normal flow of events, the software should already have in its database the information of the plots, types of crops, and equipment to be worked with; if this information is not complete, it must be entered by a user belonging to the corresponding role. In order for the agronomist to plan a planting, he only has to define the plot to be cultivated, the irrigation equipment at his disposal, and the crop to be planted. The system is then able to calculate the water and nutrient requirements and set the values at which the machine must be configured to provide them as accurately as possible. In addition, if there are already records of previous crops in that plot, the software will allow access to them, so the application becomes an additional support for decision-making. In case of need, a change in any soil or crop value can be introduced at any time; the application will then instantly recalculate all the necessary values, using the weighted averages of the historical data in the case where some of the variables involved are incomplete. In this way, dynamism is provided that allows the adjustment of the planning to the changing conditions originated by meteorological situations, the updating of the bibliography, or others that are characteristic of a real sowing. Using this system, the agronomic design was carried out on a field with the same characteristics as the one that had undergone the agronomic design manually. The results are shown in **Table 3.**

Table 3. Automated agronomic design used for bean cultivation.

CC (days)	ARH (m^3/ha)	ARV (m^3 /turn)	IR (days)	RM (%)	AEH (m^3/ha)	AEV (m^3/turn)	Difference		
							(m^3/turn)	(m^3/crop cycle)	%
-		12,760.4		15.7	364.3	12,737.0	–23.4		
0–30	183	6397.7		31.3	182.7	6388.9	–8.8	–88.2	99.9%
31–60	244	8530.2		23.4	244.4	8545.8	15.5	116.5	100.2%
61–90		9439.2		21.10	271.1	9477.3	38.1	285.8	100.4%
91–	242	8460.32		23.7	241.6	8444.7	–15.6	–116.9	99.8%

CC- Crop cycle. ARH - Water required per hectare. ARV - Water required per turn. IR - Irrigation interval. RM - Regulation of the machine used. AEH - Water delivered per hectare. AEV - Water delivered per turn.

As can be seen in the table above, the differences between the water required per crop cycle and that delivered by the system using the proposed software are never greater than 0.5%. This value implies that only a fraction of the water that was wasted with the manual estimations was over- or under-used. For example, in the cycle between days 61 and 90, the machine used 5217.8 m^3 too much when using the values calculated by hand, whereas, in the same cycle, it used only 285.8 m^3 too much when using the numbers provided by the application. In terms of water economy, it can be stated that there was a saving of wasted water of up to 94.5% (4932.0 m^3). In addition, it is necessary to evaluate the influence of this practice on the final yield of the crop, since the values supplied are more in line with its real needs, meaning that a sowing, according to the evapotranspiration values, is in a better condition to reach its optimum yield.

Figure 4 shows the comparison between the real needs of the crop in each of its phases, against the quantities of water provided to the crop using both the traditional calculation method and the values provided by the assisted configuration system.

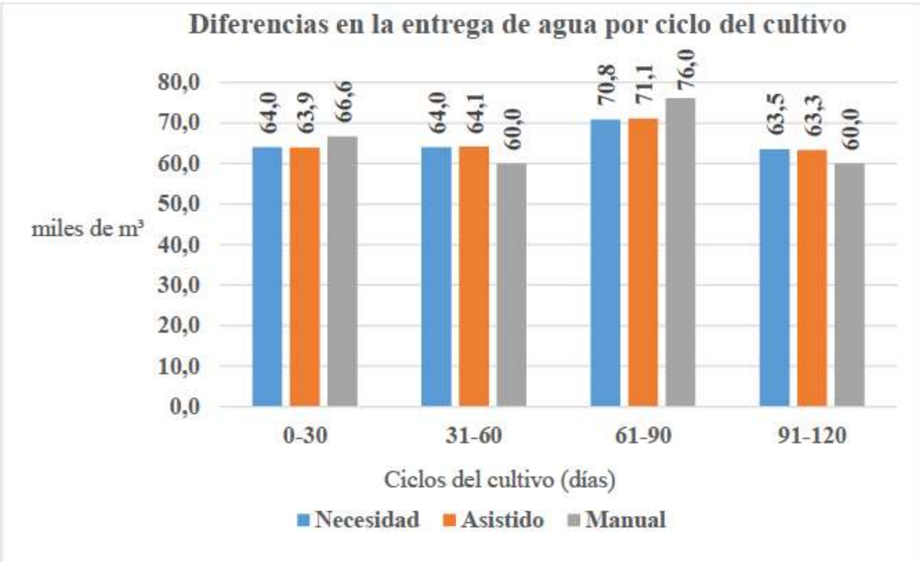

Figure 4. Comparative graph of the results of the application of the configuration values returned by the proposed software, compared to the manual configuration.

As can be seen, without the use of the application, the values used for irrigation were markedly higher or lower than those calculated for the crop in each of its phases. However, the values obtained with the use of the software are considerably closer to the theoretical values required.

5. Conclusions

As a result of the present research, a computer system was presented that enables software-assisted irrigation through the fast and reliable configuration of irrigation equipment present in Cuba and constitutes a fundamental step in the implementation of practices related to precision agriculture. The proposed system was validated by means of an experimental study in the agricultural enterprise "La Cuba", in bean cultivation, reaching a saving of water used unnecessarily of up to 94.5%, which allowed obtaining a better use of the irrigation machine used. As an added value, the software presents a minimalist, intuitive, and attractive interface that allows real-time visualization of field information through the use of augmented reality techniques. Based on these results, the incorporation of artificial intelligence techniques that contribute to decision-making in the process of preparing irrigation plans is a future task.

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Conflict of interest

The authors declare no conflict of interest.

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