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Development of a New Control Algorithm for Automatic Irrigation Scheduling in Soilless Culture

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Abstract: In soilless culture, water and nutrients must be frequently and precisely applied due to the reduced volume and low water holding capacity of the substrate. For this reason, irrigation scheduling is an important and difficult task. The use of an irrigation control tray with two electrodes (level sensor) is a simple way for controlling irrigation. Irrigation operation is triggered when the water level in the tray decreases below a preset level. This is a simple on-off control but inflexible because it requires periodic manually calibrations. This work aims at developing a more efficient control system for the irrigation management of soilless culture. The control system is based on a Proportional Integral Derivative (PID) algorithm and it allows for fully automatic operation with a minimum set of variables in order to reduce the cost of the equipment. The results obtained demonstrate that the PID control algorithm can efficiently be used to control irrigation in soilless culture. The calculated average daily leaching fractions fit reasonably well to the target values. Nevertheless, some improvements of the control algorithm are required to reduce the variability of the calculated leaching fractions during the initial stage of crop development.

Keywords: Irrigation scheduling, substrate culture, irrigation control tray, PID controller

1 Introduction

Automatic control algorithms are successfully used in industrial processes. Nowadays, the application of optimal control techniques and evolutionary algorithms to the management of water systems is an active field of research.

These methods have also been applied to the management of irrigation systems. For example, Several authors [24,16,19] developed algorithms for the optimal irrigation scheduling of irrigation districts. Montesinos et al., see [13], applied an evolutionary algorithm to the optimal management of furrow irrigation. Nevertheless, few of these works have been specifically applied to the irrigation scheduling control of soilless crops.

Soilless culture [25] is a growing technique largely used in greenhouse horticulture in the Mediterranean basin of Spain. The use of this technique is increasing because of soil salinization and overexploitation, and the presence of soil pathogens [3]. Economic reasons also exist behind this change. Soilless culture can provide higher yields and improved product quality due to the greater control of the production process.

In substrate culture, water and nutrients must be precisely applied to the crop because the water holding capacity of the substrate is very low and substrates are usually inert. If the volume of water absorbed exceeds the allowable water depletion of the substrate, the crop may suffer severe stress and yield reduction. For this reason, the irrigation periods must be very short and frequent.

The irrigation water applied must satisfy crop water consumption and an additional amount of water to prevent salt accumulation in the substrate [21,10]. Nevertheless, if excessive water were to be drained from the substrate, there would be losses of water and nutrients, thereby increasing the operational costs and producing environmental damage due to groundwater pollution [8].

For these reasons, the development of an efficient irrigation scheduling method for substrate culture is of great importance. Currently, various irrigation scheduling

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methods are being developed and tested to optimise the water use efficiency in soilless cultures.

Some irrigation scheduling methods are based on the application of a water balance. These methods require accurate estimation of the consumption of water by the crop. These irrigation water needs are usually calculated by modelling the crop transpiration using climatic data obtained under greenhouse conditions [23,12,17,2,5,18, 11].

Lizárraga et al., see [9], assessed the performance of two different irrigation scheduling methods for hydroponic tomato production in Navarra, northern Spain.

Other irrigation scheduling methods are based on measurement of the water status of the substrate, either as substrate moisture, using granular matrix sensors or capacitive sensors [15] or as substrate water potential, using tensiometer or electrotensiometer [4].

An alternative procedure is to use an irrigation control tray, which is a simple but effective method of automatically controlling irrigation scheduling in substrate crops [4]. The most widespread irrigation control tray used in greenhouse crops in southern Spain works with a level sensor relay. Several units that contain the growing medium (i.e., grow bags or rock-wool slabs) are placed on the tray. This type of tray contains two electrodes placed at different heights. One electrode is constantly submerged. When the level of water decreases by a specified level due to the water consumption of the plants in the control unit, the second electrode is exposed and an electrical signal triggers irrigation. This tray works as a simple on-off control system. The level of the second electrode has to be manually set to obtain the leaching fraction that ensures the adequate removal of salts from the substrate. This is one of the main disadvantages of this type of irrigation control tray. In addition, this manual calibration needs to be carried out periodically as the crop roots grow or when changes in the leaching fraction are desired.

To overcome these limitations, new optimal control methods are being researched. Sigrimis et al., see [20], proposed an optimisation-based method for irrigation control of soilless culture under greenhouse climatic conditions.

In this work, the main objective is to develop an automatic irrigation scheduling control system for soilless culture based on the use of a Proportional Integral Derivative (PID) controller and a control tray. This control system is intended to be robust and use a minimum set of control variables to reduce cost. In the irrigation control tray used, the volume of water drained is measured rather than the water level in the tray. Measuring of the volume of water applied and drained allows the leaching fraction to be accurately calculated. The PID controller uses information regarding past and current deviations of the actual leaching fractions to the target leaching fraction to regulate the intervals between irrigations. The basic assumption made in this work is that the very high irrigation frequency used in substrate culture makes this process almost continuous; thus, a PID controller can be a suitable option to control this process.

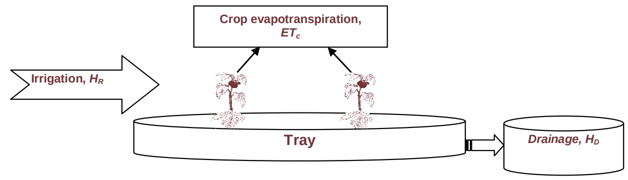

Fig. 1: Water balance in the irrigation control system

The testing and calibration of the proposed control algorithm has been performed by a by developing a crop simulation model that reproduces the behaviour of a real crop and a water balance model that simulates the performance of the control tray. This procedure allows us to simulate under greenhouse climatic conditions, the water consumption of the most extended crops in the area and the response of the PID algorithm to these simulated water demands. With this procedure many expensive and time consuming field experiments have been avoided.

Finally, an optimization algorithm has been used to tune the PID control algorithm parameters.

The proposed automatic irrigation control model has been implemented in a computer program.

2 Methodology

2.1 Proposed irrigation scheduling control system

The proposed irrigation scheduling control system is illustrated in Figure 1. The water input to the tray is represented by the applied irrigation depth (H_R). The outputs of water from the system are the drainage depth from the tray (H_D) and crop water consumption. Crop water consumption is determined by evapotranspiration (ET_c).

In a real experiment, H_R can be calculated as a function of the emitter discharge (q), number of emitters per tray (n_e), irrigation time (t_r), number of plants per tray (n_p), and plant spacing (S).

$$H_R = \frac{n_e \cdot q \cdot t_r}{S \cdot n_p} \tag{1}$$

Experimentally, H_D can be measured by using a tipping bucket gauge (similar to a pluviometric gauge) or gravimetrically (for example using a load cell).

The following water balance equation can be written for this system:

$$H_R - ET_c = H_D \tag{2}$$

The leaching fraction (LF) is defined as the ratio of the water drained to the water applied. Knowing both variables, the leaching fraction can be calculated using the following equation:

$$LF = \frac{H_D}{H_R} \tag{3}$$

The objective of irrigation management in substrate culture is to provide the volume of water consumed by the crop plus an additional target leaching volume in order to refill the water withdrawn from the substrate by the crop and maintain the salt concentration in the substrate within allowable limits [21].

To avoid crop water stress, it is necessary to limit the maximum amount of water taken up by the crop from the substrate to the allowable water depletion (P_r). It is usually expressed as a fraction of the total available water in the substrate (TAW_s). TAW_s is usually expressed as a fraction of the total substrate volume (V_s). The allowable water depth in the substrate (H_{ac}) can be calculated using the following equation:

$$H_{ac} = \frac{TAW_s \cdot V_s \cdot P_r}{S \cdot n_p} \tag{4}$$

The usual irrigation scheduling strategy in substrate culture is to apply a constant irrigation water depth for all the irrigation operations equal to the allowable water in the substrate plus a drainage depth. As the water consumed by the crops is variable depending on the crop status and the climatic conditions, the length of the intervals between two irrigation events are consequently variable. The irrigation water is calculated using the following equation:

$$H_R = H_{ac} + H_D = H_{ac} + LF \cdot H_R \tag{5}$$

Finally, H_R can be calculated as a function of H_{ac} and the desired LF:

$$H_R = \frac{H_{ac}}{1 - LF} \tag{6}$$

The desired LF is established in order to maintain an appropriate salt concentration in the root environment. Methods to calculate this required LF are proposed in specific literature [22].

The accurate estimation of the length of the interval between two irrigation events is very important to obtain the desired LF. For this purpose, a radiation sensor is commonly used. Using the radiation measurement, it is possible to estimate ET_c and determine the appropriate irrigation time. In the proposed model in this work, rather than using a radiation sensor or other complex or expensive devices, the length of the interval between two irrigation events is estimated using only the water input and output information provided by the tray and the proposed PID controller.

If the length of the interval between two irrigation events is correctly estimated, the plant water consumption (ET_c) during that period will be equal to the allowable water depletion in the substrate (H_{ac}), and the resulting LF will coincide exactly with the required or target leaching fraction (LF_c). If the irrigation interval were longer or shorter, the resulting leaching fractions would be lower or higher and the salt concentration in the root environment would not be optimal. This would result in a yield reduction that could be estimated using methods available in the literature [22].

2.2 Model framework

This works aims at testing the adequacy of the proposed PID controller to properly manage the irrigation scheduling in a substrate culture and at calibrating its parameters.

The proposed control model is composed of two main submodels: a PID based irrigation control simulation model and a PID calibration model. The first one comprises a crop simulation model to estimate the water uptake of the crop for a given period, a water balance in the tray to calculate the drainage water volume and the resulting leaching fraction and a PID controller to calculate the length of intervals between two irrigation events.

The calibration model provides the optimal PID parameters values that best fit the resulting leaching fractions to the target or required leaching fraction. Both models can be run independently.

The basic scheme of the model is depicted in the following flowchart:

2.2.1 Irrigation controller simulation model

Crop simulation model

A crop simulation model was developed to calculate the crop water consumption for each irrigation interval.

The first step is to calculate daily crop evapotranspiration (ET_c). The methodology proposed by Fernández et al., see [7], was used for this purpose. Crop evapotranspiration can be calculated using the following equation [6]:

$$ET_c = ET_o \cdot K_c \tag{7}$$

Where ET_o is the reference evapotranspiration and K_c is the crop coefficient.

Reference evapotranspiration (ET_o) was calculated using measured daily pan evaporation data from a Class A evaporation pan located inside an experimental greenhouse in the local agricultural research center ”Las Palmerillas” (Almería, Spain). The following equation was applied:

$$ET_o = K_{pan} \cdot E_o \tag{8}$$

Where K_{pan} is the pan coefficient and E_o is the evaporation from a free water surface.

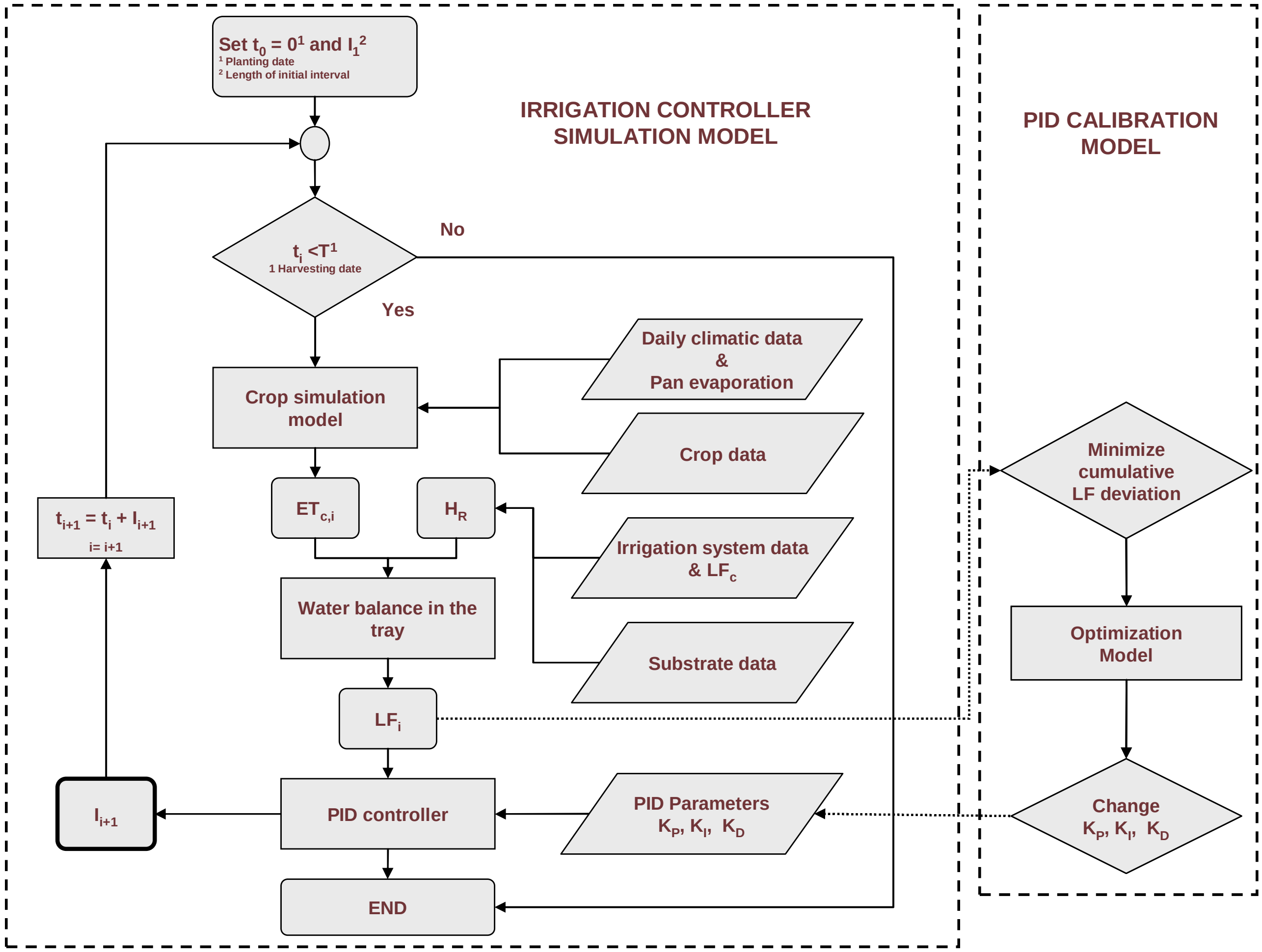

Fig. 2: Flowchart of the proposed irrigation control model

The value used for K_{pan} was the proposed by Fernández et al., see [7], for greenhouse climatic conditions ($K_{pan} = 0.79$).

To calculate crop coefficients (K_c) for the most common horticultural greenhouse crops along their development stage, the model proposed by Fernández et al., see [7], was used. Empirical relationships for the estimation of the K_c values as a function of the cumulative thermal time for the major horticultural greenhouse crops in southern Spain were proposed by these authors.

With the aim of simulating the water consumption of the plant between two consecutive irrigation events, it is necessary to disaggregate the calculated daily crop evapotranspiration into shorter time periods. As no experimental climatic data were available for periods shorter than a day, the proposed model assumes that the fraction of the water consumption during a specific time interval to the daily water consumption is directly related to the fraction of the incoming extraterrestrial solar radiation (R_a) during that period. As the extraterrestrial solar radiation for daily or shorter periods can be calculated from the solar constant, solar declination and time of the year using appropriate astronomical equations [1], the equation used to disaggregate the daily crop water evapotranspiration ($ET_{c,d}$) in shorter periods ($ET_{c,t}$) is as follows:

$$ET_{c,t} = ET_{c,d} \frac{R_{a,t}}{R_{a,d}} \tag{9}$$

Where: $R_{a,d}$ is the daily extraterrestrial solar radiation and $R_{a,t}$ is extraterrestrial solar radiation during the interval between irrigation t.

PID based irrigation control model

An algorithm based on a PID controller is used to estimate the irrigation interval. The aim of this work is that the PID controller uses information regarding past and current deviations of the actual leaching fractions to the target leaching fraction to regulate the irrigation intervals. The basic assumption made in this work is that the very high irrigation frequency used in substrate culture makes this process almost continuous. The aim of this work is to test the suitability of the proposed PID based controller to control this process.

The PID controller proposed in this paper calculates the time interval between irrigations using the following equation:

$$I_{i+1} = I_i + K_P\left(LF_i - LF_c\right) + K_I \sum_{k=i-m+1}^{i} I_k\left(LF_k - LF_c\right) + K_D\left(\frac{\left(LF_i - LF_c\right) - \left(LF_{i-1} - LF_c\right)}{I_i}\right) \quad (10)$$

Where: I is the length of the intervals between two consecutive irrigations (in minutes). Subscript i, $i+1$ and $i-1$ refers to the current, next and previous irrigation events respectively and subscript k is used to calculate the integral of the leaching fraction deviations of the m preceding irrigation events. The number of previous irrigation events, m, is a parameter of the control algorithm and must be set by the user. Finally, K_P, K_I, K_D are the proportional, integral and derivative gains of the PID controller, respectively.

Equation (10) provides an estimation of the time interval between irrigations for the $i+1^{th}$ irrigation event from the previous time interval between irrigations and leaching fractions whose values are known.

The resulting leaching fraction for the present time interval can be calculated using the water balance model, see equations (2) and (3).

2.2.2 PID calibration model

To apply the model in practice to a real crop, it is necessary to tune the parameters of the control algorithm previously. Tuning a control loop is the adjustment of its control parameters (proportional gain, integral gain and derivative gain) to the optimum values for the desired control response.

The adjustment of control parameters using an experimental procedure is not feasible due to the very high experimental time and cost. In this work, a crop simulation model has been preferred to simulate the behaviour of the control system under not real but simulated crop water requirements.

The water consumption for a given period is calculated using the proposed crop simulation model. The irrigation water input per irrigation event is calculated using equation (6), for a given target leaching fraction. Knowing the volume of irrigation water and the simulated consumption of the crop, the resulting drainage water volume and leaching fraction can be calculated by applying the equation (2) of water balance in the tray.

The mean square error (F) between the leaching fraction provided by the simulation model for all the irrigation operations and the target leaching fraction was used to evaluate the performance of the control algorithm.

$$F = \sqrt{\frac{\sum_{i=1}^{n}\left(LF_i - LF_c\right)^2}{n}} \quad (11)$$

Where LF_i is the leaching fraction provided by the model for the i^{th} irrigation event and n is the total number of irrigations.

An optimization algorithm was used to determine the values of the optimal parameter values (K_P, K_I and K_D) of the PID control algorithm that minimise the mean square error of the leaching fractions. The Nelder-Mead Simplex optimization algorithm [14] was used in this work. This is a technique for minimising an objective function in a many-dimensional space.

3 Results and discussion

3.1 Software application development

A new software tool has been developed to implement the proposed methodology. This tool is able to simulate the performance of a PID controller for the automated control of the irrigation operations in a substrate culture, under simulated crop water demands. The software provides the irrigation times, the length of the irrigation intervals and the resulting leaching fractions.

In addition, the developed tool allows tuning of the optimal parameters of the PID control algorithm to obtain the best fit between the leaching fraction estimates and the target leaching fraction using an optimisation method.

The main control algorithm has been programmed using the Visual Basic for Applications programming language embedded in a Microsoft Excel spreadsheet file.

The user interface has been designed using a Microsoft Excel worksheet. It is organised into several frames, in which basic model parameters, crop data, irrigation system data and substrate characteristics are introduced. From the main Visual Basic program and using the ActiveX Data Objects (ADO) technology, the program can perform queries to a database implemented in Microsoft Access to retrieve the input data needed by the model. The input database tables are a climate database (which stores the weather variables), a crop database (which stores the agronomic features of each crop) and a substrate database (which stores the physical characteristics of the substrates).

The data required by the model are the following:

3.1.1 Model parameters

The values of the three parameters used by the PID algorithm (K_P, K_I and K_D) can be either explicitly defined as input parameters or their optimal values can be calculated using the optimisation module. The target leaching fraction (LF_c) and the length of the initial interval (I_1) must be also defined. The model allows the user to change the required leaching fraction along the crop growing cycle.

3.1.2 Crop data

The user must select the type of crop to simulate. The main horticultural greenhouse crops in southern Spain are available in the crop database. Once the crop has been selected, the agronomical data needed by the model are retrieved by querying the crop database. The plant spacing and the dates of planting and harvesting of the crop have to be defined.

3.1.3 Irrigation System Data

Basic irrigation system data must be provided to the model: emitter spacing, emitter discharge and irrigation uniformity.

3.1.4 Substrate data

The user can select the type of substrate to simulate. After selecting the substrate, the physical data for the substrate are retrieved by the program by performing a query to the substrate database. This database contains the majority of substrates used in soilless culture. The desired water depletion of the substrate, the volume of the substrate bag, the number of bags per tray and the number of plants per tray must also be specified.

3.1.5 Climate data

The climate data used in the model were taken from the Experimental Station ”Las Palmerillas” located in the centre of the study area at 37 N of latitude. This research centre has a weather station placed on a turf inside a typical plastic-covered greenhouse. Pan evaporation and temperature data inside the greenhouse were used for this study.

3.2 Experimental evaluation of the crop simulation model

The crop simulation model used in this work is based on the methodology proposed by Fenández et al., see [7], to calculate the daily crop evapotranspiration. These authors demonstrated that the estimation of the daily crop evapotranspiration from daily pan evaporation data following their methodology is pretty accurate. They obtained a regression coefficient (r^2) value of 0.98 when they compared the measured and estimated daily ET_o values and also found a good fit between the measured and estimated K_c values.

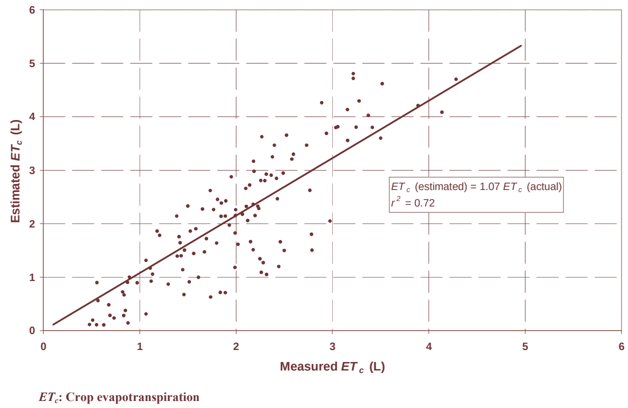

Fig. 3: Estimated versus measured ET_c values between two consecutive irrigations

With the aim of testing the accuracy of the proposed methodology to disaggregate the daily crop evapotranspiration into shorter periods, actual crop water consumption data for a tomato crop have been experimentally obtained and compared to the estimated ones. The actual water consumption data have been obtained for a real tomato crop measuring the irrigation water input and drainage output volumes for every irrigation event, see equation (2). The actual crop water consumption for a specific interval between two consecutive irrigations can be obtained subtracting the drainage volume to the irrigation water volume in the final irrigation event of each period. The experimental period was between March 20 and April 14, 2013. Figure 3 shows the comparison between the measured and estimated ET_c values between irrigations.

As expected, a satisfactory correlation has been found between the ET_c values measured between two irrigation events and the estimated values provided by the proposed crop simulation model, because the evapotranspiration inside a greenhouse is mainly related to solar radiation. However, a lag between ET_c and incoming radiation has been experimentally observed. This fact has been pointed out by other researches [22]. [12] stated that the observed hysteresis of the transpiration with the radiation may have been related to the thermal inertia of the greenhouse. In fact, crop water consumption has been measured even in the night time when there is no direct solar radiation. Nevertheless, only daylight irrigation periods have been considered in the previous analysis.

These results demonstrate that the proposed simulation model is accurate enough to be used as a tool with the aim of assessing the performance of the irrigation scheduling control model.

3.3 Performance of the control model

In order to evaluate the performance of the model, a simulated case study was analysed. In this case study, tomato was chosen as it is the most extended crop in the area. The selected planting date was on February, 15 and the harvesting date was on June, 22. A plant density of 2 $plants \cdot m^{-2}$ was considered and the number of plants per tray was 4. The selected substrate was perlite. The number of bags per tray was 2 with a volume of 10 $L \cdot bag^{-1}$.

The first step was to run the PID calibration model to get the optimal values of the parameters of the control algorithm for the proposed case study. The values of the parameters provided by the model that minimised the deviations from the target leaching fraction in the case study were as follows: $K_P = 60$, $K_I = 200$ and $K_D = 2$. The model was then run with the estimated optimal values and an initial time interval of 450 minutes.

To evaluate the performance of the model under different management conditions, a sensitivity analysis has been performed for several values of target leaching fraction, LF_c and allowable water depletion, P_r. The results provided by the model are summarized in table 1, where n s the mumber or irrigation, H_R is the irrigation depth, I is the average length or the irrigation interval, LF is the average simulated leaching fraction and F is de mean square error.

Table 1: Results of the performance of the model

LF_c	P_r	n	H_R (mm)	I (min)	LF	F
0.30	0.025	1628	416.9	44.4	0.305	0.066
0.30	0.050	806	412.8	88.0	0.308	0.053
0.30	0.075	538	413.3	128.2	0.312	0.069
0.30	0.100	404	413.8	167.1	0.314	0.081
0.25	0.025	1659	396.5	43.6	0.269	0.090
0.25	0.050	822	392.9	86.3	0.273	0.065
0.25	0.075	553	396.5	124.8	0.282	0.089
0.25	0.100	414	395.8	163.2	0.283	0.095
0.20	0.025	1697	380.2	42.6	0.236	0.116
0.20	0.050	842	377.3	84.5	0.242	0.085
0.20	0.075	568	381.8	121.4	0.255	0.109
0.20	0.100	427	382.7	158.2	0.259	0.117

As it is shown in Table 1, the obtained F values were lower for higher LF_c and lower P_r values. This means that the model performs better for these working conditions. This seems to be reasonable because in these conditions the irrigation operations are more short and frequent and the PID control works more efficiently. From an agronomical point of view, lower P_r values are appropriate for the crop development because the water depletion in the substrate is low and the risk of water stress is lower. However, required leaching fractions to maintain the salt balance in the substrate depend on the electrical conductivity of the irrigation water and the salt tolerance of the crop and they should not be too much high with the aim of saving water and nutrients. The conclusion is that the performance of the algorithm should be improved for the cases where low LF_c values are used.

In the following paragraphs, the results provided by the model for a LF_c value of 0.3 and a P_r value of 0.05 are discussed. Figure 4 shows the simulated daily crop water consumption along the growing cycle. The daily average water consumption was 2.32 $L \cdot m^{-2}$, with a maximum of 7.57 $L \cdot m^{-2}$ and a minimum of 0.16 $L \cdot m^{-2}$. As observed from the graph, the water demand increases as the crop develops. The number of irrigations events ranged from less than 1 irrigation per day in the early stages of the crop to 21 irrigations per day when the crop is fully developed.

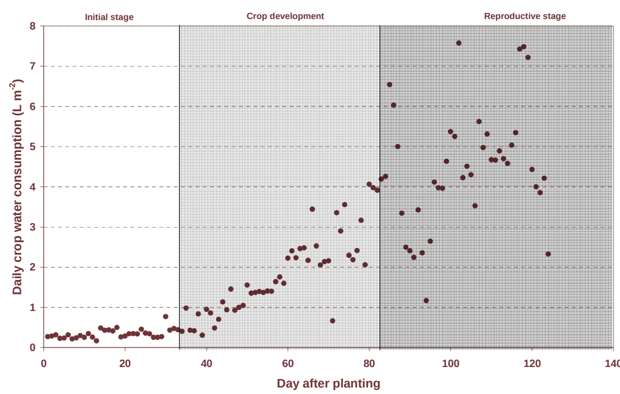

Fig. 4: Daily water consumption provided by the crop simulation model

Figure 5 shows the length of the interval between two irrigation periods provided by the model. Model execution resulted in 806 irrigations, representing an average of 7 irrigations per day. The average value of time between irrigations throughout the entire growing season was 88 minutes. As shown in Figure 5, the initial interval was 450 minutes, and during the first stage of the crop development in which crop water consumption was low, the irrigation intervals were longer. The irrigation needs grow higher as the crop leaf area increase; consequently, the time between irrigations becomes shorter. In the middle of the growing season, there were several consecutive cloudy days in which the irrigation needs of the crop were lower. The proposed control algorithm responded efficiently to these changing crop demands by increasing the duration of the irrigation intervals. The model also responded fairly well to the cyclic daily variations in water demands. In the last stages of the crop growing season, the length of the intervals also exhibits cyclic variation.

Figure 6 shows the average daily leaching fractions throughout the entire growing season.

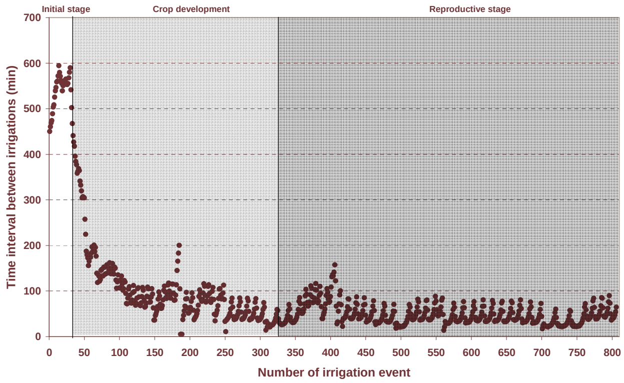

Fig. 5: Time intervals between irrigations provided by the model

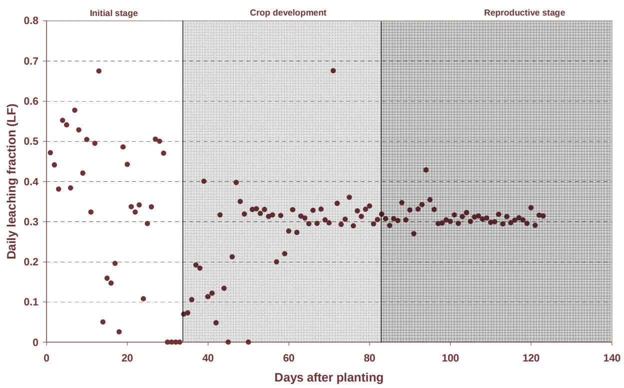

Fig. 6: Daily leaching fractions provided by the model

The resulting average leaching fraction for the entire growing period was 30.75%. The relative deviation from the target leaching fraction (30% in this case) was 2.5%.

These results can be considered satisfactory as the model adjusted fairly well the target leaching fraction during most of the growing cycle. Nevertheless, as the graph shows, the *LF* deviations from the target *LF* were much higher in the first stage of crop development. This can be due to the low water consumption of the crop at the beginning of the growing season that resulted in very large irrigation intervals. These large irrigation intervals made the response of the controller to be slower than desired and, for this reason, there is a lag between the actions taken by the controller and the crop needs. These rapid *LF* variations can produce short-term changes in the salt concentration in the substrate that can be especially detrimental for the crop. Some researchers have pointed out that a sudden increase of the electrical conductivity in the root environment strongly will reduce the water absorption, because of the reduced difference between the osmotic potential of the internal and external solution [22]. Besides, the crop is more sensitive to abiotic stresses in the first part of the growing cycle. Furthermore, along the early stage of the crop, some *LF* values resulted equal to zero. This entails that the applied irrigation water depth was in fact lower than the crop water consumption and as a consequence there was not any drainage flow. This fact is undesirable as the crop can undergo a severe water and saline stress.

Table 2 summarizes the contribution of the proportional, integral and derivative terms of the PID controller. As it is shown in this table, the most relevant component was the proportional term. The mean correction of the time interval between irrigations ($|\Delta I|_{mean}$) was 9 minutes which represents approximately a 10% of the mean irrigation time interval (I_{mean}) along the growing period (88 minutes). The integral component had a much lower contribution as its mean correction was less than a minute (0.33% of the mean time interval). The contribution of the derivative controller can be considered absolutely negligible.

Table 2: Contribution of the Proportional, Integral and Derivative components

	Proportional	Integral	Derivative
ΔI_{Max} (min)	30.80	1.52	0.05
ΔI_{min} (min)	-55.24	-2.57	-0.17
$\lvert\Delta I\rvert_{mean}$ (min)	9.06	0.29	0.005
$\lvert\Delta I\rvert_{mean}/I_{mean}$ (%)	10.29	0.33	0.01

Taken the results obtained in this work as a basis, future research and developments are expected to be done in this research line to improve the performance of the irrigation control model. It is necessary to implement some modifications in the algorithm to allow a more rapid response of the controller to the low and changing irrigation needs, especially in the early stages of the crop development. A salt balance in the tray is going to be implemented in order to estimate the salt concentration in the substrate and the yield response of the crop. Finally, a field research program is going to be carried out to test the proposed methodology experimentally.

4 Conclusions

A simple and low cost automatic control system based on a PID algorithm has been developed for optimal irrigation management in soilless cultures.

The automatic control system developed requires a very low number of variables to operate as the irrigation input and the drainage output volumes of water to the irrigation system. These variables are easily measurable, and there is no need to measure weather data or using expensive climatic sensors to control the irrigation efficiently.

The proposed model has performed well when applied to a case study. In this case study, the model was tested under the simulated demands of a common horticultural greenhouse crop in the Mediterranean Basin of Spain. The leaching fractions were fairly well adjusted to the target leaching fraction. However, there is some variability in the leaching fractions when single irrigation operations are considered; this occurs especially in the early stages of crop development when the water needs are low and the resulting irrigation intervals are large. Some improvements to the proposed model should be introduced to reduce this variability before performing a field experiment.

5 Notation

The following symbols are used in this paper:

E_o	Evaporation from a free water surface
ET_c	Crop evapotranspiration
$ET_{c,d}$	Daily crop evapotranspiration
$ET_{c,t}$	ET_c during the irrigation interval t
ET_o	Reference evapotranspiration
F	Mean square error
H_{ac}	Allowable water depth in the substrate
H_D	Drainage depth
H_R	Irrigation depth
I	Time interval between irrigations
K_c	Crop coefficient
K_D	Derivative gain of the PID controller
K_I	Integral gain of the PID controller
K_P	Proportional gain of the PID controller
K_{pan}	Pan coefficient
LF	Leaching fraction
LF_c	Target leaching fraction
LF_t	Simulated LF for the t^{th} irrigation event
m	Number of previous irrigation events
n	Total number of irrigation operations
n_e	Number of emitters per tray
n_p	Number of plants per tray
P_r	Allowable water depletion
q	Emitter discharge
r^2	Coefficient of regression
R_a	Extraterrestrial solar radiation
$R_{a,d}$	Daily extraterrestrial solar radiation
$R_{a,t}$	R_a during the interval irrigation t
S	Plant spacing
TAW_s	Total available water in the substrate (Fraction)
t_r	Irrigation time
V_s	Substrate volume

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