BIOSYSTEMS ENGINEERING 153 (2017) 70–81

Available online at www.sciencedirect.com

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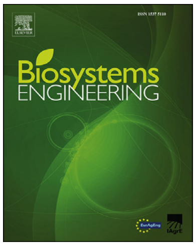
journal homepage: www.elsevier.com/locate/issn/15375110



Research Paper

Wireless sensor networks for greenhouse climate and plant condition assessment

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ARTICLE INFO

Article history:
Received 25 May 2016
Received in revised form
9 November 2016
Accepted 14 November 2016
Published online 27 November 2016

Keywords:
Climate heterogeneity
Plant-based measurements
Precision agriculture
Climate control

Spatially distributed environmental measurements at plant level can be used to create a precise and detailed representation of the climate at various regions inside a greenhouse. Climatic heterogeneity can cause significant differences in terms of yield, productivity, quantitative and qualitative characteristics of the plants, as well as the development of various diseases. This work presents: i) the assessment of wireless sensor networks (WSNs) operation reliability and accuracy in actual greenhouse conditions, ii) the development of a distributed monitoring system using a WSN in a commercial greenhouse, and iii) the analysis of the collected spatially distributed data for the investigation of possible problematic situations for the growing plants caused by climatic heterogeneity inside the greenhouse. A prototype WSN was initially developed in order to investigate the effects of the environmental conditions to the operation reliability of the network and assess its performance and the feasibility of its operation in a commercial greenhouse. The enhanced WSN was then installed in a commercial greenhouse to investigate the spatial variation of the existing environmental conditions. Analysis based on WSN measurements showed significant spatial variability in temperature and humidity with average differences up to 3.3 °C and 9% relative humidity and transpiration, with the greatest variability occurring during daytime in the summer period. There were conditions that favoured condensation on leaf surfaces and other problematic situations.

1. Introduction

The existence of strongly coupled factors affecting the greenhouse environmental conditions makes climate control a complex task. In addition, spatial heterogeneity which is inherent to the biological and physical aspects of the involved processes and systems, makes the optimal control task even more challenging. In modern greenhouses, several measurement points at plant level are required to create an objective and detailed view of the climate at various regions in the entire greenhouse space. Specific climatic gradients can cause significant differences in terms of yield, and quantitative and qualitative characteristics of the plants, as well as the development of various diseases. To be able to eliminate these

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http://dx.doi.org/10.1016/j.biosystemseng.2016.11.005

Nomenclature

a	Constant defined in Eq. (2), dimensionless
b	Constant defined in Eq. (2), W m^{-2} kPa^{-1}
BS	Base-station
CEA	Controlled environment agriculture
MRD	Mean relative deviation
N	Number of measurements
PA	Precision agriculture
R	Radiation intensity, W m^{-2}
R^2	Determination coefficient
RMSE	Root mean squared errors
Std	Standard deviation
Tr	Transpiration, W m^{-2}
VPD	Vapour pressure deficit, kPa
WSN	Wireless sensor network

differences, a precise and accurate distributed monitoring system is required.

With the relatively recent advancement of wireless sensor networks (WSNs), such distributed monitoring is technically and economically feasible. These networks usually consist of battery-powered nodes equipped with specific sensors that collect appropriate information and transmit it wirelessly to a central base-station (BS), which stores the received data for future processing or uses it dynamically for monitoring, control and other purposes, e.g., data analysis, forecasting (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002; Li, Sha, & Lin, 2014; López; Riquelme et al., 2009; Matese, Di Gennaro, Zaldei, Genesio, & Vaccari, 2009; Vox et al., 2014). The main properties that are crucial to the proper operation of a WSN are: i) sufficient accuracy of measurements, ii) reliable network connectivity and iii) low power consumption. The importance of other aspects of proper WSN operation, like data security, depends on each specific application. Several network architectures, communication protocols and energy-management algorithms have been applied to WSNs to maximise sensing coverage of the network as well as life-duration of the battery-powered sensor nodes (Ghiasi, Srivastava, Yang, & Sarrafzadeh, 2002; Krishnamachari & Ordonez, 2003). These properties are affected not only by the characteristics of the sensors and the design parameters and communication algorithms of the network, but also by the environmental and physical conditions that the WSN operates in.

Precision agriculture (PA) and controlled environment agriculture (CEA) introduce several application-specific parameters that have to be considered alongside communication-specific and energy-specific properties, when designing a WSN (Baggio, 2005; Ferentinos & Tsiligiridis, 2007; Garcia-Sanchez, Garcia-Sanchez, & Garcia-Haro, 2011; Mancuso & Bustaffa, 2006). The use of WSNs in such applications provides valuable information about the spatial distribution of the monitored variables, which constitutes a very important tool for precise control mainly in PA, but also in large-scale CEA (Balendonck, Van Os, & Schoor). Especially in the case of CEA, which mainly involves the monitoring and control of greenhouse environment, several issues can arise in relation to the sensing quality of the WSNs used, mainly because of the extreme environmental conditions inside a greenhouse (Ferentinos, Katsoulas, Tzounis, Kittas, & Bartzanas, 2015). Such conditions can make the WSN measurements noisy and usually associated with some measure of uncertainty (Katsoulas, Ferentinos, Tzounis, Bartzanas, & Kittas, 2015a; Wen, Xiao, Markham, & Trigoni, 2015). Ahonen, Virrankoski, and Elmusrati (2008) developed a WSN specifically for a commercial greenhouse facility, measuring temperature, humidity, solar radiation and CO_2 concentration. They performed several tests and concluded on the specific issues that arise in a greenhouse WSN application. Similarly, Balendonck et al. (2014) reported limitations of WSNs sensing accuracy in greenhouse environments in relation to measurement errors introduced by the effect of direct radiation exposure on the sensor nodes.

Kittas and Bartzanas (2007) reported that many researchers in greenhouse environment have considered the climate inside a greenhouse as uniform during development of climate control methodologies. However, several studies investigated the heterogeneity of greenhouse conditions (Soni, Salokhe, & Tantau, 2005; Teitel, Atias, & Barak, 2010). With the capability of multiple measuring points in a practical and cost-effective way with the WSN technology, the exploitation of climatic variability is now feasible. Several recent works have investigated the use of WSNs for the estimation of climatic variability in the greenhouse (Balendonck et al., 2014; Bojacá, Gil, & Cooman, 2009; Castillo, 2007). In addition, efforts have been made to introduce such analyses in the development of distributed greenhouse environmental control (Chaudhary, Nayse, & Waghamare, 2011; Gomes, Brito, Abreu, Gomes, & Cabral, 2015; Gonda & Cugnasca, 2006; Pawlowski et al., 2009).

The current work first investigated the operation reliability and accuracy of WSNs installed in experimental greenhouses. Specific greenhouse environmental conditions in relation to solar radiation exposure of the sensor nodes that affect the quality of measured variables in terms of accuracy were identified, and their role in the accuracy of measurements was explored and analysed. Consequently, relevant preliminary work presented in Katsoulas, Ferentinos, Tzounis, Bartzanas, and Kittas (2015b) was expanded, with a primary goal to use a fully operational WSN to detect and analyse the spatial variability of environmental and plant-related conditions inside a commercial greenhouse. This can potentially increase the possibility of detecting problematic situations for the cultivated plants, leading to environmental control methodologies capable of minimising the occurrence of problems associated with crop production. Issues relevant to energy consumption of the battery-powered sensor nodes, as well as network communication issues in greenhouse WSNs, have been addressed in our previous work (Ferentinos et al., 2015) and were not part of the current study. Finally, security of data communications for the specific greenhouse application under investigation, was not considered as a crucial factor and was not considered, mainly because no environmental control was involved and the WSNs usage was restricted to measurements reliability analysis and greenhouse climate assessment.

2. Materials and methods

2.1. *WSN reliability experiments*

The initial experiments for the investigation of the operation reliability and accuracy of WSNs in greenhouse conditions were conducted in one of the experimental greenhouses of the University of Thessaly, Velestino, Greece (39° 44′ N, 22° 79′ E). The conventional, single-span, arched greenhouse that was used, has plastic cover (polyethylene film) and a ground area of 160 m^2 (20 m in length by 8 m in width). Natural ventilation is achieved through two side openings and a roof opening. The greenhouse is equipped with air mixers and a fog system. Finally, the central sensors system includes temperature and relative humidity sensors HD9009TR Hygro-transmitter (Delta OHM, S.r.L., Padova, Italy) (accuracy $T = \pm 0.1$ °C, Relative Humidity $= \pm 2\%$) and a CM-6 solar pyranometer (Kipp & Zonen, Delft, The Netherlands), located at the centre of the greenhouse, at approximately 1.8 m above ground. During the experiments, there were no cultivated plants in the greenhouse, so that the effects of solely the outside environmental disturbances to the greenhouse microclimate can be considered, as they affect the operation reliability of the installed WSN.

The WSN prototype was based on the open source, low-power TelosB platform, by UC Berkeley (Berkeley, CA, USA), with TinyOS operating system. Specifically, the motes CM3000 (Advanticsys, Spain) were used. Wireless communication was achieved with a CC2420 Radio Frequency chip (Texas Instruments, USA). In the WSN base-station a mote CM3300 by Advanticsys was used, which contains an amplifier for the wireless circuit that offers greater communication range. The base-station also included a PC for the collection, storage and processing of the acquired data. The CM3300 node was connected via a Universal Serial Bus (USB1000) board (by Advanticsys) to a USB port of a personal computer. The main computational units of the wireless nodes were safely enclosed in IP65 humidity resistant boxes and external sensor modules were connected to them. For the air temperature and relative humidity, a Sensirion's SHT75 sensor was selected for its high performance, low power consumption and high precision. For the radiation intensity measurements, SP Lite2 pyranometers were used (Kipp & Zonen, Delft, The Netherlands), connected to a Wisensys® wireless measuring platform that wirelessly transmitted the measured values to a central base-station. In all the experiments, each node of the WSN communicated directly with the base-station (i.e. single-hop communication), without the use of any cluster head nodes in between. The base-station node was at about 20 m from the wireless nodes of the network.

Three specially designed experiments were conducted with specific WSN setups inside the greenhouse, each with specific goals concerning the identification of the effects of greenhouse environmental conditions to sensing reliability and quality of the WSN. In all cases, the main goal was to identify the effect of solar radiation on the accuracy of measurements of the network's sensors and for that reason, three different placements of the WSN nodes were considered: i) inside mechanically ventilated boxes specially designed to protect the sensors and the wireless nodes from solar radiation, labelled as "boxed nodes", ii) under the shade of some metallic surface, labelled as "shaded nodes" and iii) unprotected from direct sunlight, labelled as "exposed nodes". Temperature and relative humidity values were measured by the wireless nodes, while radiation intensity levels were also recorded at the place of each wireless node. In addition, values of temperature, relative humidity and radiation intensity from the central sensors of the greenhouse control unit were also recorded. The WSN and the portable radiation intensity units were taking measurements every 30 s and reporting averaged values every 2 min. Those measurements were averaged over 10-min periods to match the time-step of the central control unit of the greenhouse. All sensor nodes were calibrated against industrial-grade sensors. For this purpose, the effect of greenhouse environmental conditions (air temperature, relative humidity and radiation intensity) on the quality of measured variables was identified and its effect in the accuracy of measurements was explored and analysed. Specific compensation algorithms were then proposed and used for the calibration of wireless sensors towards more reliable and accurate monitoring of greenhouse climatic conditions, so that the properly tuned WSN could be then used for precise measurements. Details on the calibration process and sensor placements in the greenhouse can be found in Katsoulas et al. (2015a).

The main goal of the experiments was to investigate the accuracy and reliability of measurements as influenced by sunlight inside the greenhouse. Three different experiments were designed and conducted during a 4-month period, from September to December. During the 1st experiment, four "boxed" nodes were placed at the four corners of the 20 m by 8 m greenhouse, 3 m away from the sides, at a height of about 1.8 m, and measurements were collected for a period of one week. In the 2nd experiment, the "exposed nodes" setup was used for the same four nodes, while radiation intensity was also measured at the points of the sensor nodes. The experiment lasted for 12 days. Two approaches were followed in the effort to determine in which degree the reliability of the sensor's readings is influenced by solar radiation inside the greenhouse: a) the standard deviations of the measurements between the 4 WSN nodes in each experiment (boxed and exposed nodes) were estimated and correlated with the radiation intensity values, and b) the root mean squared errors (RMSEs) of the WSN measurements based on the greenhouse central sensors were estimated and were also correlated to the radiation intensity values. Subsequently, the 3rd experiment was conducted with the goal of investigating the accuracy and reliability of carefully shaded sensor nodes, by comparing their measurements with those of "boxed" sensor nodes. Two groups of two nodes each were used, one with "boxed" nodes and one with "shaded" nodes. For each group, the standard deviations between the nodes of the group and their RMSEs based on the greenhouse central sensors were determined and correlated to radiation intensity levels. This specific experiment lasted for 18 days.

2.2. *Greenhouse climate heterogeneity assessment experiments*

The second set of the experiments were conducted in a commercial greenhouse in Pirgetos, Central Greece (39° 55′ N, 22° 35′ E). The conventional, 5-span, arched greenhouse that was used, has glass covered walls and single film polyethylene covered roof. The greenhouse ground area is of 0.5 ha (105 m long by 48 m wide). It was equipped with a wet pad/fans system located along the long side wall of the greenhouse; roof windows, a heating system with floor and plant-level heating pipes, and recirculating air fans located 4 m above ground. Each span had a separate operating zone of the heating and irrigation system. During the experiments, cucumber plants were cultivated in a hydroponic system using rockwool. The crop rows were parallel to the long side of the greenhouse (North–South) and crosswise to the air flow generated by the cooling system.

The WSN consisted of 5 wireless sensor nodes placed at specific points that covered the entire area of the greenhouse. The measured variables were air temperature, relative humidity and leaf temperature. The wireless nodes were Zolertia Z1 (Zolertia, Spain) equipped with the SHT11 (Sensirion, Switzerland) air temperature and humidity sensors and the Zytemp TN9 (Zytemp, Taiwan) air and surface temperature infrared thermocouple sensors. They used single-hop communication to transmit data to the central base-station of the network, which was an Advanticsys CM3300 node (Advanticsys, Spain) connected to an embedded Olimex OlinuXino A13 (Olimex, Bulgaria) computer running Debian Linux. The WSN nodes were placed symmetrically at canopy level (1.5 m height) at the positions shown in Fig. 1. Because the WSN was experimental and was solely used for environmental monitoring purposes and not any advanced tasks, like, e.g., distributed climate control, the number of sensors was considered to be sufficient to represent the specific area. This assumption was justified by the results, considering the degree of variation of the measured values in relation to sensors' accuracy.

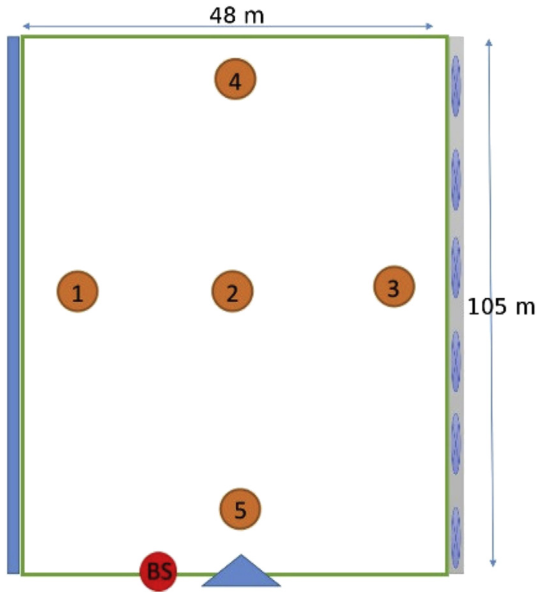

Fig. 1 – WSN nodes layout, measuring air temperature, relative humidity and leaf temperature inside the greenhouse. Wet-pad on the left side (West) and fans on the right side (East). Greenhouse entrance and WSN base-station (BS) on the bottom side (South).

This set of experiments was conducted during two different periods: i) a "winter period" from February 12 to March 18, 2015 and ii) a "summer period" from May 1 to July 17, 2015. Measurements were sent to the WSN base-station every 2 min and then averaged over 10-min intervals. It should be noted that some periods of problematic operation of the WSN occurred during the experiments, producing sparse time gaps in the registered measurements that ranged in duration, from several minutes to entire days. The reasons for the failure of the WSN are under investigation. The possible effect of crop canopy and high values of air relative humidity on the signal strength of the wireless node will be investigated in the future. Thus, there were some sampling discontinuities in the data used for the analysis presented here.

The spatial variability of each measured environmental variable was estimated based on the readings of the 5 sensor nodes using the following metrics:

- The maximum difference between the values of the 5 sensors, averaged over the periods of interest (daytime and night time for each experimental period).
- The standard deviation of these averages.
- The mean relative deviation (MRD), which is estimated as follows:

$$MRD = \sum\left(|V_i - V_m|/(N \cdot V_m)\right),\ i = 1\,N \tag{1}$$

where: N is the number of measurements of a specific variable, V_i is the measurement i, and V_m is the average value of all N measurements.

The first two metrics indicate the size of variability of the measurements, in average, while *MRD* is a metric of uniformity, with lower values corresponding to better uniformity. In addition to these metrics on the average values for the specific periods of interest, several graphical representations were developed in order to depict spatial variability, after estimating the variables' values in the entire area of the greenhouse using interpolation on the measured values, based on a penalised least squares method (Garcia, 2010).

3. Results and discussion

In this section, the results on the investigation of operation reliability and accuracy of WSNs installed in experimental greenhouses are initially presented. Subsequently, the data collected during the operation of the final WSN installed in a commercial greenhouse are analysed and the results on the spatial variability of environmental and plant-related conditions the greenhouse are presented.

3.1. *WSN operation reliability*

The analysis of standard deviations between the values of the four sensor nodes during the first two of the first part of experiments, showed that variability between temperature measurements of the four sensors was much greater for higher values of radiation intensity in the case of "exposed" nodes, while in the case of "boxed" nodes the increase of standard deviation of the temperature values was very small with the increase of radiation intensity (Fig. 2a). In the case of relative humidity values (Fig. 2b), the measurements of the "boxed" nodes seem to be also highly influenced by the intensity of solar radiation, with higher deviation values in the middle values of radiation intensities, while in the case of "exposed" nodes, the spreading in not practically influenced by solar radiation. It should be noted here that there was no stationary shading on any of the WSN nodes due to structural elements, thus the structural shading was not an issue. In addition, a moving shading pattern was observed on all WSN nodes.

Analysis of RMSEs showed that, in general, the RMSE of both air temperature and relative humidity values of WSN nodes compared to the greenhouse central sensors were much higher in the case of "exposed" nodes. In the case of temperature values (Fig. 3a), there was no obvious correlation of the RMSEs of the "exposed" sensors with the values of radiation intensity, while in the case of relative humidity (Fig. 3b), the errors seem to be slightly increasing at higher radiation intensities.

Thus, temperature and relative humidity measurements reliability were heavily influenced by solar radiation intensity, making wireless sensor nodes that were not properly protected highly unreliable for measuring greenhouse environmental conditions.

In the 3rd experiment, in the case of temperature measurements, "shaded" nodes seemed to perform even better than "boxed" nodes, as the deviations between the two nodes measurements were smaller and practically not influenced by radiation intensity levels (Fig. 4a). In particular, "boxed" sensors performed rather poorly during the night as far as their variability was concerned. Similarly, the corresponding RMSEs of the "shaded" sensor nodes were slightly lower than those of the "boxed" sensors (Fig. 4b). In the case of relative humidity measurements, the standard deviations of the values showed that "shaded" nodes were influenced by solar radiation intensity, while "boxed" sensor nodes were less influenced. However, the RMSEs of the groups of sensors showed, as in the case of temperature measurements, that "shaded" sensor nodes were slightly more accurate in general than "boxed" nodes. The accuracy and reliability of measurements provided by those "shaded" nodes make the development of a compensation algorithm that would take radiation intensity levels into account, rather unnecessary.

3.2. *Climate and plant conditions assessment*

Environmental and plant-related conditions were measured during the second part of the experiments, described in Section 2.2, with a main purpose of capturing and analysing the spatial distribution and variation of the conditions of temperature and relative humidity, as well as specific plant-related conditions using the additional information provided by the leaf temperature measurements. Based on these spatially distributed measurements, several aspects of the controlled environment were analysed and are presented in the following sub-sections. Because the initial experiments indicated that simple shading is sufficient to obtain reliable measurements from WSN nodes in greenhouse environments while exposed nodes are problematic and "boxed" nodes do not provide any real advantages, simple shading was used for the sensor nodes of the WSN used in this second part of the experiments.

3.2.1. *Temperature and relative humidity spatial variability*

Based on the estimated metrics of spatial uniformity of temperature measurements (Table 1), greatest heterogeneity occurs during daytime in the summer period (max difference of 3.3 °C, standard deviation of average temperatures between the 5 sensors equal to 1.23 and MRD value equal to 0.036). Differences in temperature values can be mainly attributed to the operation of the cooling system, with the air temperature values progressively increasing from pad to fans. Nevertheless, it seems that the cooling system of the greenhouse performed quite well, although airflow was across the crop rows, since even for the case of airflow parallel to crop rows, other

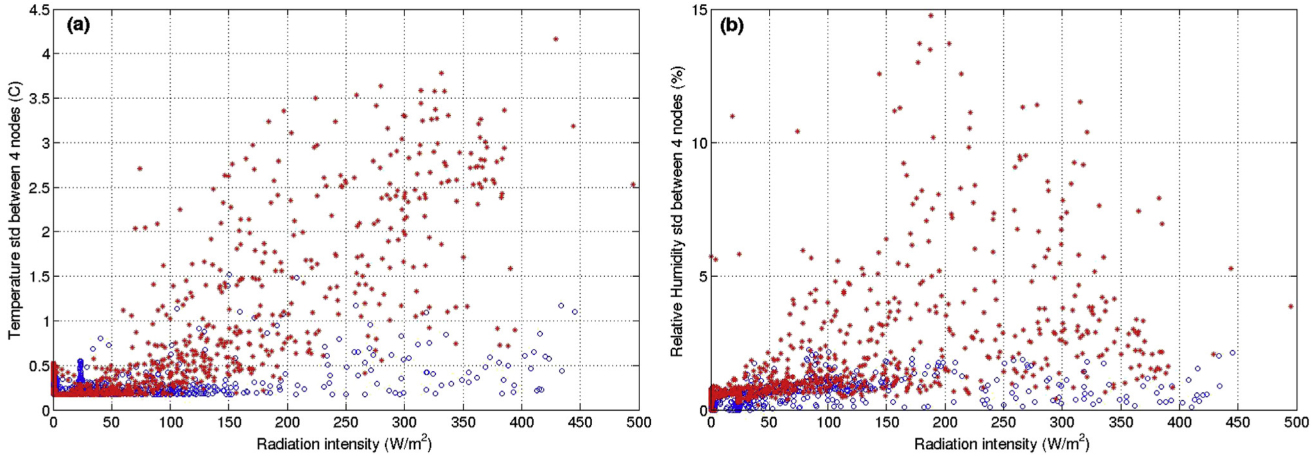

Fig. 2 – (a) Temperature and (b) relative humidity standard deviations between 4 sensor nodes versus radiation levels, in cases of "boxed" (circles) and "exposed" (stars) nodes.

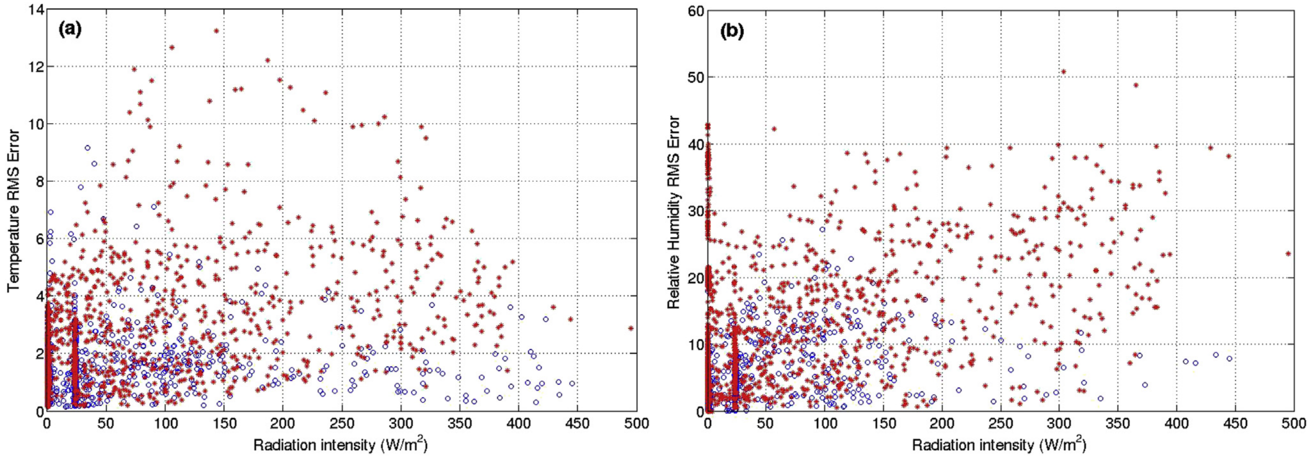

Fig. 3 – (a) Temperature and (b) relative humidity RMSEs versus radiation levels, in cases of "boxed" (circles) and "exposed" (stars) nodes.

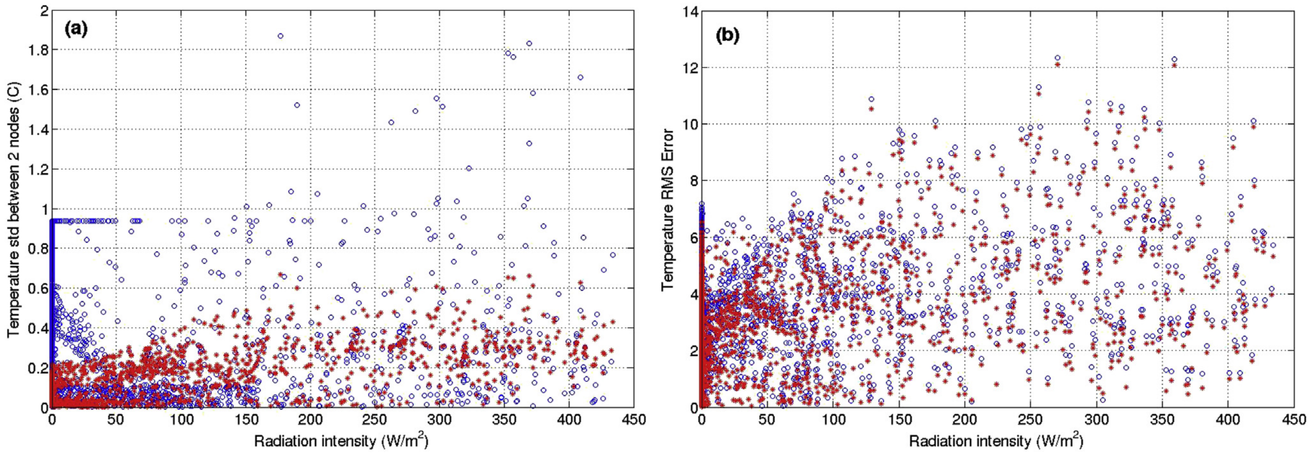

Fig. 4 – (a) Temperature standard deviations between 2 sensor nodes and (b) temperature RMSEs, versus radiation levels, in cases of "boxed" (circles) and "shaded" (stars) nodes.

Table 1 – **Average temperature values and standard deviations (Std) (°C) of each sensor for daytime and night time periods. Also, the maximum average difference, the standard deviation of the averages, and the mean relative deviation (MRD) of the averages are included.**

Sensor number (see Fig. 1)	Summer				Winter			
	Day		Night		Day		Night	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Sensor 1	23.4	4.83	17.3	3.21	20.8	5.11	16.0	1.24
Sensor 2	24.8	5.13	18.0	3.17	21.6	5.90	16.2	1.20
Sensor 3	25.6	5.04	18.7	3.34	21.0	5.69	15.5	1.47
Sensor 4	26.7	5.73	18.0	3.40	21.9	6.28	16.7	1.27
Sensor 5	24.5	4.58	18.4	3.22	21.2	5.32	15.9	1.44
Max diff.	3.3		1.4		1.1		1.2	
Avg. std	1.23		0.55		0.45		0.42	
Avg. MRD	0.036		0.022		0.017		0.019	

authors have observed similar or even greater air temperature differences (e.g. Kittas, Bartzanas, & Jaffrin, 2003; López, Valera, Molina-Aiz, & Peña, 2012). The corresponding values during night time in the summer period and during both daytime and night time in the winter period, were much lower (e.g., maximum averages temperature differences around 1 °C)., thus variability during these periods was much smaller.

In the case of relative humidity (Table 2), the highest spatial variability occurred during daytime for both periods (maximum differences around 9%, standard deviation of

Table 2 – Average relative humidity values and standard deviations (Std) (%) of each sensor for daytime and night time periods. Also, the maximum average difference, the standard deviation of the averages, and the mean relative deviation (MRD) of the averages are included.

Sensor number (see Fig. 1)	Summer				Winter			
	Day		Night		Day		Night	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Sensor 1	74.6	11.89	77.3	8.57	64.0	15.32	57.4	15.52
Sensor 2	78.6	11.95	80.3	7.99	65.5	17.32	60.5	16.98
Sensor 3	78.5	13.66	80.8	8.70	64.2	17.86	59.6	16.52
Sensor 4	69.6	13.49	78.9	8.61	68.6	15.91	60.1	16.94
Sensor 5	75.3	11.39	76.1	7.81	60.0	14.81	56.7	14.41
Max diff.	9.0		4.7		8.6		3.8	
Avg. std	3.68		1.98		3.09		1.70	
Avg. MRD	0.035		0.020		0.032		0.025	

average humidity values between the 5 sensors around 3–3.7%, and MRD values around 0.033). Although the air temperature variations appeared to be affected by the air flow from pad to fans, relative humidity variation seems to be mostly distributed along the long (North–South) direction of the greenhouse. During the night, relative humidity measurements were relatively uniform during both experimental periods (summer and winter). It should be noted that during the night, the air recirculating fans were used, something that seems to have resulted in higher microclimate homogeneity.

The surface graphs in Figs. 5 and 6 give a schematic representation of the observed variations for temperature and relative humidity, respectively. In these figures, and in those that follow, each rotated rectangle corresponds to the greenhouse layout of Fig. 1, rotated around 60° anticlockwise. Also, in all similar figures, the presented values are based on the WSN measurements at the positions of the nodes and interpolated values for the rest of the greenhouse area. It is evident that different variability exists for temperature and humidity between seasons and daytime/night time periods. However, there is a general similarity between day and night results for each period (season), for both temperature and humidity.

Figure 7 shows the evolution of uniformity of temperature and relative humidity values (expressed with the MRD metric) during both experimental periods, for daytime and night time. During night time (plots (b) and (d)) both variables present better uniformity. It is evident that during daytime the variability of both temperature and, especially, humidity, is larger (plots (a) and (c)). Thus, concerning the evolution of variability throughout the experimental periods, it seems that there is a

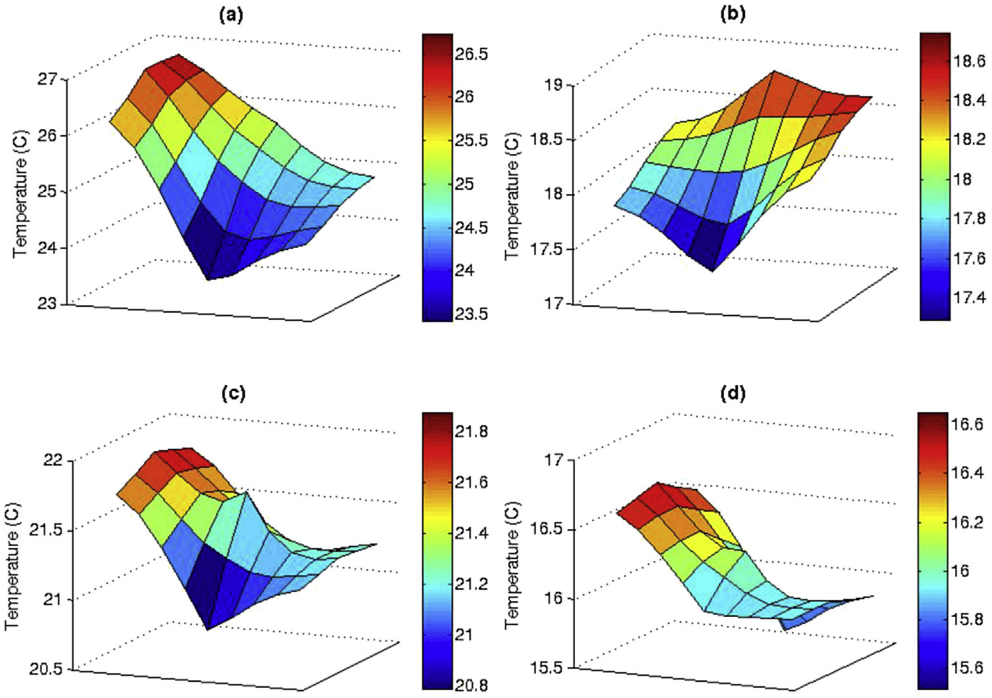

Fig. 5 – Surface plots of average temperature. (a) Summer period – daytime, (b) Summer period – night time, (c) Winter period – daytime, (d) Winter period – night time. Each rotated rectangular corresponds to the greenhouse layout of Fig. 1, rotated around 60° counterclockwise.

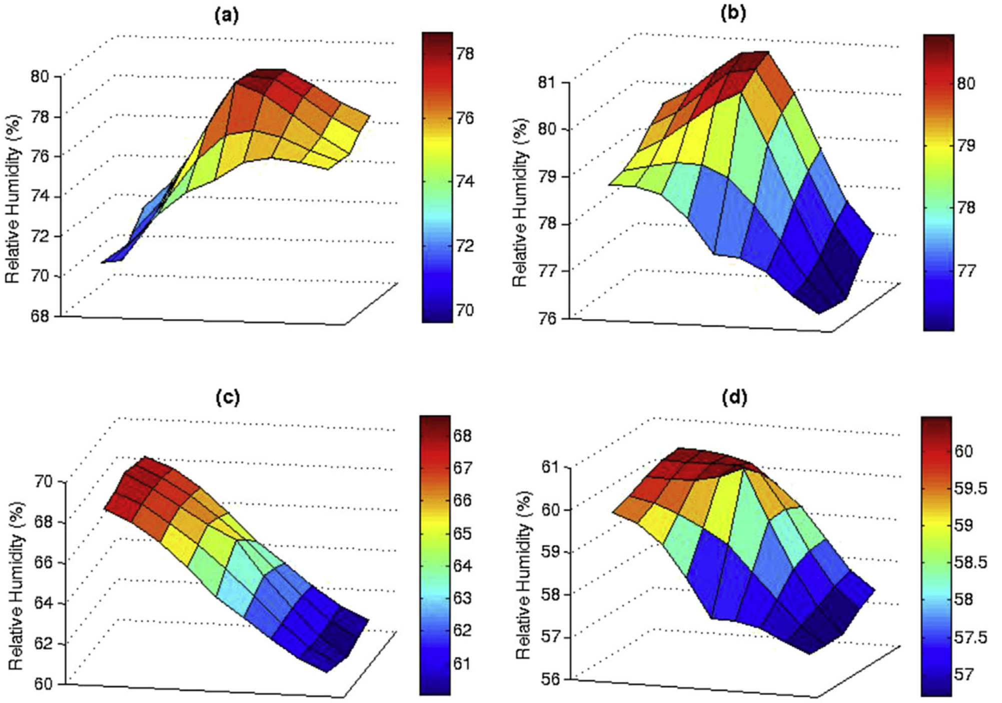

Fig. 6 – Surface plots of average relative humidity. (a) Summer period – daytime, (b) Summer period – night time, (c) Winter period – daytime, (d) Winter period – night time.

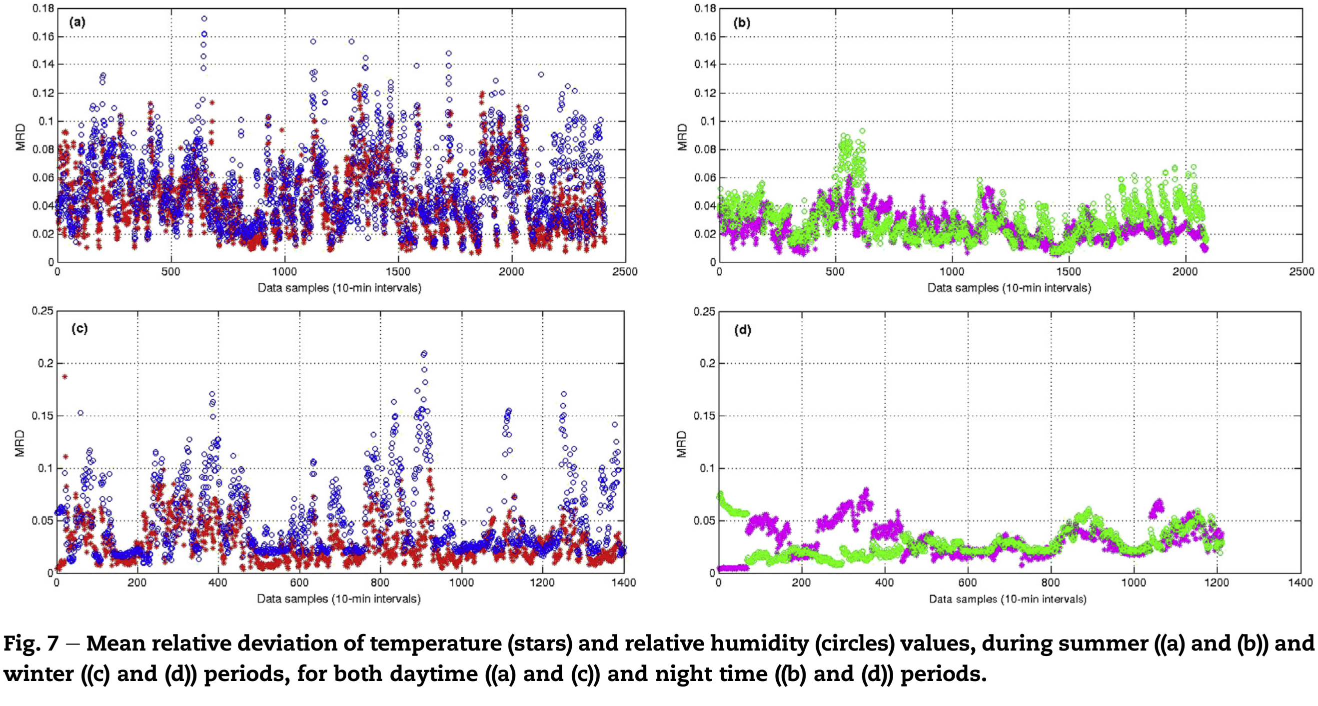

Fig. 7 – Mean relative deviation of temperature (stars) and relative humidity (circles) values, during summer ((a) and (b)) and winter ((c) and (d)) periods, for both daytime ((a) and (c)) and night time ((b) and (d)) periods.

distinction between daytime and night time, rather than between summer and winter periods.

3.2.2. *Transpiration variability*

Crop transpiration is an important parameter that can be used to optimise irrigation scheduling towards the increase of water use efficiency and consequently, water saving. Transpiration spatial variability in the cultivated plants can be used to develop sophisticated irrigation scheduling for precise, optimal water application. Here, a simple model was used to estimate transpiration (Tr) for tomato crop at the measuring points, based on the following equation:

$$Tr = a\,R + b\,VPD \tag{2}$$

where, R is the radiation intensity (W m^{-2}) (measured at the centre of the greenhouse), VPD is the vapour pressure deficit (kPa), calculated using the measured values of temperature and relative humidity, and *a* and *b* are constants (Katsoulas & Kittas, 2011).

Figure 8 shows the spatial distribution of average transpiration values over the entire summer period (for daytime (a), night time (b), and for the entire day (c)). Transpiration varies drastically along the long (North–South) direction of the greenhouse, while there is an opposite behaviour in its variability between daytime and night time. Of course, night time values are much smaller, thus the overall variability (Fig. 8c) is similar to that observed during the day. The rather smooth and clear variability along the long (North–South) direction of the greenhouse makes the development of a precise irrigation control system that takes this variability into account, feasible.

Figure 9 shows the correlation between MRD of transpiration (lower values of MRD correspond to better uniformity) and radiation intensity. It can be observed that transpiration uniformity has, in general, a proportional (exponential) correlation with light intensity, even though MRD values are quite spread out in lower light intensities, resulting in a low R^2 value (0.36). The variation of uniformity (the spreading of the dots on the vertical direction) refers to the second derivative of the variable under question (i.e., of transpiration). It should be noted that focus here is not on the decrease of the variation of uniformity, but rather on the increase of the uniformity (correlation line). The decrease of the variation of uniformity is probably caused by the *R* factor in Eq. (2), which becomes dominant over VPD as radiation increases, resulting in more similar values. Similar variations were also found by Boulard and Wang (2002) who modelled a wind induced ventilation of a tunnel greenhouse with a 3 m s^{-1} wind of normal incidence to the structure. Their model computed the level of crop transpiration on the one side of the greenhouse (North side) to be 30% smaller than other locations because of lower solar energy and air speed. Similar results were also observed by Fatnassi, Boulard, Poncet, and Chave (2006) who simulated crop transpiration in a multispan greenhouse.

3.2.3. *Condensation conditions risk*

The measured leaf temperature values of the cucumber plants were used to identify periods with conditions that favoured condensation on the surface of the leaves (when leaf temperature was less than or equal to dew point temperature). Thus, dew point temperatures were dynamically calculated for each WSN node position and compared to leaf temperatures to detect possible condensation conditions on the leaf surface. Figure 10 shows the percentage of time (based on the total number of available measurements for each experimental period) that condensation conditions existed in the different positions inside the greenhouse. It seems that during the summer period, there is a difference between wet-pad and fans sides of the greenhouse, with the latter having longer periods of condensation conditions. However, the significantly longer periods of condensation conditions that occurred during the winter period, with their different spatial distributions (Fig. 10b), made the overall (average) frequency distribution quite different, with larger variability occurring along the long side of the greenhouse (Fig. 10c). The area close to the entrance of the greenhouse had, in general, less than half the period of condensation conditions compared to the other side of the greenhouse.

3.2.4. *Problematic relative humidity conditions*

The distributed structure of the WSN provided the ability to dynamically detect even more problematic regions in the greenhouse area. One such case that was investigated was that of conditions related to relative humidity levels. Ideal conditions for the cucumber plants require values of relative humidity above 65%. During the experiments, there was a relatively high frequency of occurrence of conditions with relative humidity <65%, especially during the winter period. Problematic areas were mainly distributed along the long side of the greenhouse, with the greenhouse entrance side having 1.5 times greater frequency of occurrence than the opposite side during winter period (overall, during up to 60% of the entire period of the experiment). During simmer period, spatial variation of the problem areas was distributed along the opposite direction, but with significantly lower frequency of occurrence. Thus, the total average frequencies of occurrence during the entire experimental period show a distribution with relatively low variation, with lower occurrence frequencies towards the middle of the greenhouse, but just 6–8% lower than that towards the edges.

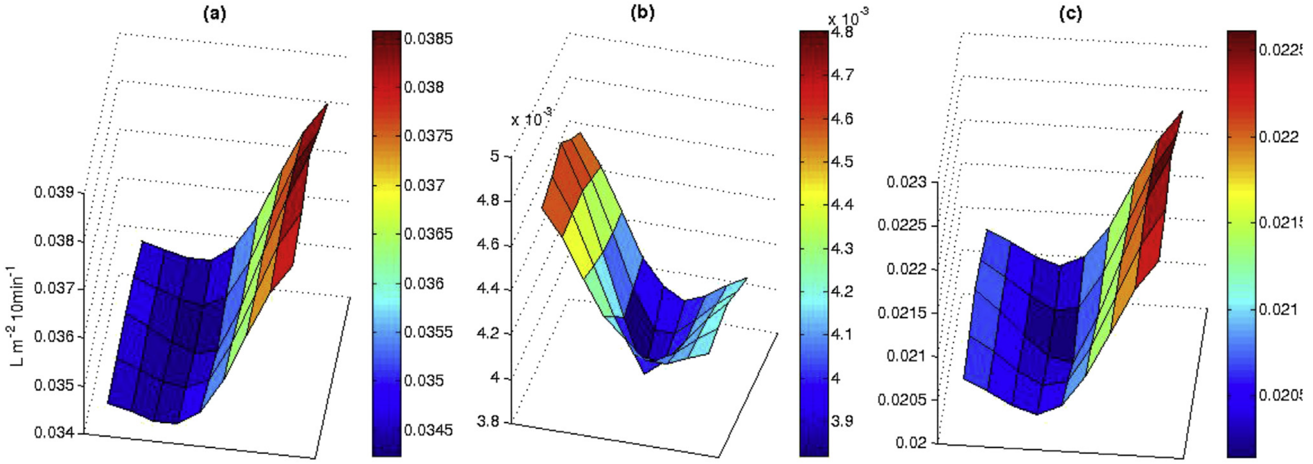

Fig. 8 – Surface plots of average transpiration. (a) Daytime, (b) Night time, (c) On average during the entire summer period.

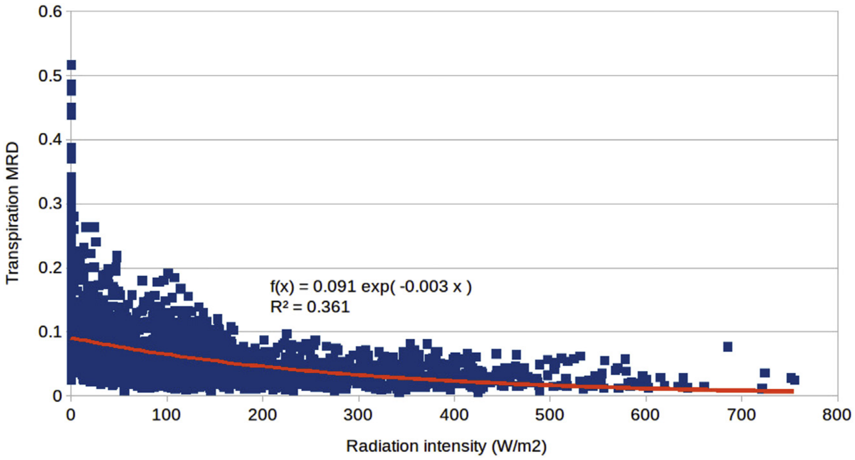

Fig. 9 – Mean relative deviation of transpiration correlation with radiation intensity.

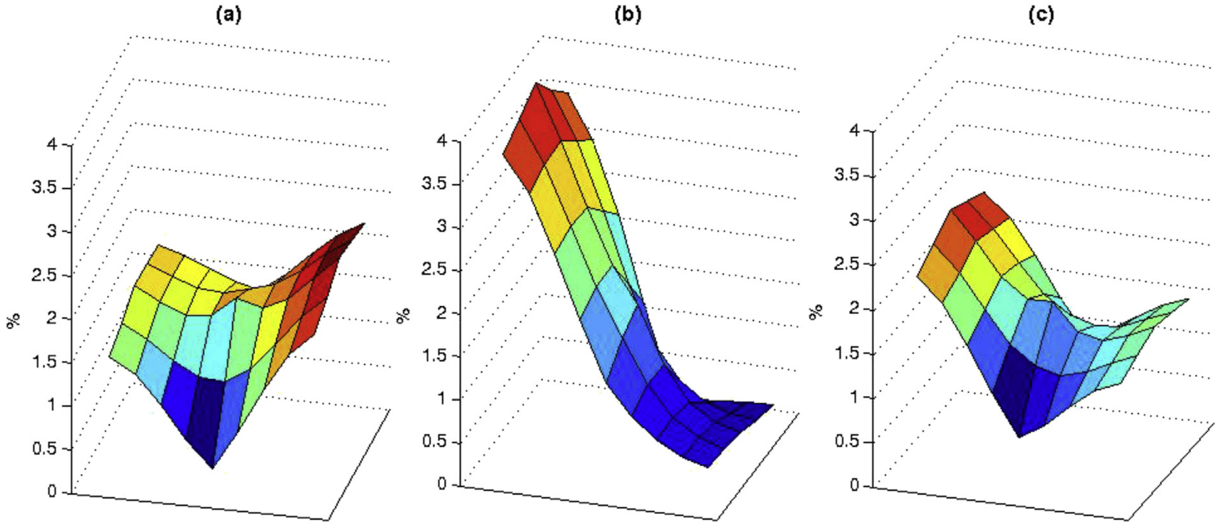

Fig. 10 – Surface plots of time percentages of condensation conditions existence. (a) Summer period, (b) Winter period, (c) On average during the entire experiment.

By analysing the spatiotemporal distribution of problematic conditions related to relative humidity inside the greenhouse, it was evident that different humidity control methodologies should be adopted during summer and winter periods, so that problem areas can minimised.

3.2.5. *Spatial variation of vapour pressure deficit*

One of the most important parameters affecting the development of greenhouse cultivation, which can be used for the development of optimal greenhouse climate control methodologies, is vapour pressure deficit (VPD). VPD was estimated based on the temperature and relative humidity values measured by the WSN. Using two-dimensional interpolation, variation of average VPD values per experimental period (summer/winter) and by time of day (day/night) was estimated. Spatial distribution of the variation inside the greenhouse shows a clear distinction in its orientation between summer and winter periods. On the other hand, the difference between day and night concerned mainly the levels of VPD and not their spatial variation inside the greenhouse, which remained relatively constant during each experimental period.

4. Conclusions

A prototype WSN was developed and installed inside a greenhouse in order to investigate the effects of actual greenhouse conditions on the operation reliability of the sensor network measurements. It was shown that reliability of temperature and relative humidity measurements is drastically influenced by solar radiation intensity, making the protection of wireless sensor nodes from high levels of solar radiation a necessity. However, experiments with different levels of shading protection showed that drastic measures are not necessary since simple shading of the wireless sensor nodes under a metallic surface was sufficient in providing protection that provided accurate and stable measurements; even more reliable than those provided by nodes enclosed in highly protective, mechanically ventilated boxes.

Consequently, an adequately built WSN was developed and installed inside a commercial greenhouse to investigate the spatial heterogeneity of the existing environmental conditions, by estimating and analysing the spatial variability of air temperature and relative humidity values, measured with a wireless sensor network, which additionally measured leaf temperature of the cultivated cucumber plants. The distributed measurements acquired by the wireless nodes were analysed to represent the spatial variation of the environmental conditions. Spatial representation of temperature and humidity values for different seasons and periods of the day, showed differences in average up to 3.3 °C and 9% relative humidity, with the greatest variability occurring during daytime in the summer period.

Spatial variability in crop transpiration was analysed in order to examine the possibility of applying precise irrigation control that could reduce water consumption. It was found that transpiration levels varied regularly along the long side of the greenhouse, making the development of such precise irrigation control systems feasible. In addition, using leaf temperature measurements, the frequency of occurrence of conditions that favoured condensation on the leaves of the plants was investigated. It was found that there were areas within the greenhouse with up to 36 times greater frequency of occurrence of such conditions than others, with the greatest variability occurring during the winter period. Finally, analysis of the spatiotemporal variation of problematic situations related to relative humidity, and VPD heterogeneity in specific regions of the greenhouse, showed clear distinctions between summer and winter periods, a fact that can provide an insight to the development of specialised climate control methodologies.

All these observations can be used, some more efficiently than others, to develop sophisticated, precise environmental and irrigation control systems that can lead to more uniform conditions for the plants, and thus more uniform quantity and quality of produce, while minimising the risk of diseases in specific problem areas of the greenhouse, and efficiently reducing irrigation water consumption. However, in order to exploit fully the spatially distributed nature of measurements that a WSN offers, the actuators and other relevant mechanical equipment of greenhouses need to be developed in such a distributed and advanced way that allows the realisation of distributed control. In future work, the design and development of such systems will be investigated, based on even more dense WSNs.

Acknowledgments

This work has been co-financed by the European Union and Greek National Funds through the Operational Programme “Education and Lifelong Learning” of the National Strategic Reference Framework (NSRF) – ARISTEIA “GreenSense” project (GN 2632).

REFERENCES

Ahonen, T., Virrankoski, R., & Elmusrati, M.. (2008). Greenhouse monitoring with wireless sensor network. IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications, 403–408.

Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., & Cayirci, E. (2002). Wireless sensor networks: A survey. *Computer Networks, 38*(4), 393–422.

Baggio, A. (2005). Wireless sensor networks in precision agriculture. In *Workshop on real-world wireless sensor networks* (pp. 107–108).

Balendonck, J., Sapounas, A. A., Kempkes, F., van Os, E. A., Schoor, R., et al. (2014). Using a wireless sensor network to determine climate heterogeneity of a greenhouse environment. *Acta Horticulturae, 1037*, 539–546.

Balendonck, J., Van Os, E. A., & Schoor, R. (2010). Monitoring spatial and temporal distribution of temperature and relative humidity in greenhouses based on wireless sensor technology. In *AgEng 2010: Towards environmental technologies, Clermont-Ferrand, France*.

Bojacá, C. R., Gil, R., & Cooman, A. (2009). Use of geostatistical and crop growth modelling to assess the variability of greenhouse tomato yield caused by spatial temperature variations. *Computers and Electronics in Agriculture, 65*(2), 219–227.

Boulard, T., & Wang, S. (2002). Experimental and numerical studies on the heterogeneity of crop transpiration in a plastic tunnel. *Computers and Electronics in Agriculture, 34*(1), 173–190.

Castillo, C. (2007). *Implementation of a prototype wireless sensors network for greenhouses*. Quito, Ecuador: UPN. Doctoral dissertation.

Chaudhary, D., Nayse, S., & Waghamare, L. M. (2011). Application of wireless sensor networks for greenhouse parameter control in precision agriculture. *International Journal of Wireless and Mobile Networks, 3*(1), 140–149.

Fatnassi, H., Boulard, T., Poncet, C., & Chave, M. (2006). Optimisation of greenhouse insect screening with computational fluid dynamics. *Biosystems Engineering, 93*(3), 301–312.

Ferentinos, K. P., Katsoulas, N., Tzounis, A., Kittas, C., & Bartzanas, T. (2015). A climate control methodology based on wireless sensor networks in greenhouses. *Acta Horticulturae, 1107*, 75–82.

Ferentinos, K. P., & Tsiligiridis, T. A. (2007). Adaptive design optimization of wireless sensor networks using genetic algorithms. *Computer Networks, 51*(4), 1031–1051.

Garcia, D. (2010). Robust smoothing of gridded data in one and higher dimensions with missing values. *Computational Statistics and Data Analysis, 54*(4), 1167–1178.

Garcia-Sanchez, A. J., Garcia-Sanchez, F., & Garcia-Haro, J. (2011). Wireless sensor network deployment for integrating video-surveillance and data-monitoring in precision agriculture over distributed crops. *Computers and Electronics in Agriculture, 75*(2), 288–303.

Ghiasi, S., Srivastava, A., Yang, X., & Sarrafzadeh, M. (2002). Optimal energy aware clustering in sensor networks. *Sensors, 2*(7), 258–269.

Gomes, T., Brito, J., Abreu, H., Gomes, H., & Cabral, J.. (2015). GreenMon: An efficient wireless sensor network monitoring solution for greenhouses. 2015 IEEE International Conference on Industrial Technology (ICIT), 2192–2197.

Gonda, L., & Cugnasca, C. E.. (2006). A proposal of greenhouse control using wireless sensor networks. Computer in Agriculture and Natural Resources, 4th World Congress Conference, 229–233, Orlando, FL, USA.

Katsoulas, N., Ferentinos, K. P., Tzounis, A., Bartzanas, T., & Kittas, C.. (2015a). Operation reliability of wireless sensor networks in greenhouse conditions. Acta Horticulturae, in press. (Proceedings of the ISHS International Symposium on New Technologies and Management for Greenhouses, GreenSys2015, 19-23 July, Evora, Protugal).

Katsoulas, N., Ferentinos, K. P., Tzounis, A., Bartzanas, T., & Kittas, C.. (2015b). Spatially distributed greenhouse climate control based on wireless sensor network measurements. Acta Horticulturae, in press. (Proceedings of the ISHS International Symposium on Modelling for Horticulture-Model IT, 11-14 October 2015, Wageningen, The Netherlands).

Katsoulas, N., & Kittas, C. (2011). Greenhouse crop transpiration modelling. In G. Gerosa (Ed.), *Evapotraspiration – from measurements to agricultural environmental applications* (pp. 311–328). Rijeka, Croatia: InTech.

Kittas, C., & Bartzanas, T. (2007). Greenhouse microclimate and dehumidification effectiveness under different ventilator configurations. *Building and Environment, 42*(10), 3774–3784.

Kittas, C., Bartzanas, T., & Jaffrin, A. (2003). Temperature gradients in a partially shaded large greenhouse equipped with evaporative cooling pads. *Biosystems Engineering, 85*(1), 87–94.

Krishnamachari, B., & Ordonez, F.. (2003). Analysis of energy-efficient, fair routing in wireless sensor networks through non-linear optimization. 2003 IEEE 58th Vehicular Technology Conference. VTC 2003-Fall (IEEE Cat. No.03CH37484), 5, 2844–2848.

Li, R., Sha, X., & Lin, K.. (2014). Smart greenhouse: A real-time mobile intelligent monitoring system based on WSN. 2014 International Wireless Communications and Mobile Computing Conference (IWCMC), 1152–1156.

López, A., Valera, D. L., Molina-Aiz, F. D., & Peña, A. (2012). Sonic anemometry to evaluate airflow characteristics and temperature distribution in empty Mediterranean greenhouses equipped with pad-fan and fog systems. *Biosystems Engineering, 113*(4), 334–350.

Mancuso, M., & Bustaffa, F. (2006). A wireless sensors network for monitoring environmental variables in a tomato greenhouse. In *WFCS 2006: 2006 IEEE International workshop on factory communication systems*.

Matese, A., Di Gennaro, S. F., Zaldei, A., Genesio, L., & Vaccari, F. P. (2009). A wireless sensor network for precision viticulture: The NAV system. *Computers and Electronics in Agriculture, 69*(1), 51–58.

Pawlowski, A., Guzman, J. L., Rodríguez, F., Berenguel, M., Sánchez, J., & Dormido, S. (2009). Simulation of greenhouse climate monitoring and control with wireless sensor network and event-based control. *Sensors, 9*(1), 232–252.

Riquelme, J. A. L. ópez, Soto, F., Suardíaz, J., Sánchez, P., Iborra, A., & Vera, J. A. (2009). Wireless sensor networks for precision horticulture in Southern Spain. *Computers and Electronics in Agriculture, 68*(1), 25–35.

Soni, P., Salokhe, V. M., & Tantau, H. J. (2005). Effect of screen mesh size on vertical temperature distribution in naturally ventilated tropical greenhouses. *Biosystems Engineering, 92*(4), 469–482.

Teitel, M., Atias, M., & Barak, M. (2010). Gradients of temperature, humidity and CO_2 along a fan-ventilated greenhouse. *Biosystems Engineering, 106*(2), 166–174.

Vox, G., Losito, P., Valente, F., Consoletti, R., Scarascia-Mugnozza, G., Schettini, E., et al. (2014). A wireless telecommunications network for real-time monitoring of greenhouse microclimate. *Journal of Agricultural Engineering, 45*(2), 70–79.

Wen, H., Xiao, Z., Markham, A., & Trigoni, N. (2015). Accuracy estimation for sensor systems. *IEEE Transactions on Mobile Computing, 14*(7), 1330–1343.