Spatially distributed greenhouse climate control based on wireless sensor network measurements

N. Katsoulas[1,2,a], K.P. Ferentinos[2], A. Tzounis[1], T. Bartzanas[2] and C. Kittas[1,2]

[1]Department of Agriculture, Crop Production & Rural Environment , University of Thessaly, Volos, Greece;
[2]Institute for Research & Technology - Thessaly, Centre for Research and Technology - Hellas, Volos, Greece.

Abstract

In modern greenhouses, several measurement points at plant level are required to create an objective and detailed view of the climate at various regions around the covered space. Specific climatic gradients 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 the development of a distributed monitoring system using a wireless sensor network (WSN) in a commercial greenhouse, towards the realization of a spatially distributed control methodology, based on specific spatial variations of the measured environmental variables. The distributed measurements acquired by the wireless nodes are analysed to represent the spatial variation of the environmental conditions inside the greenhouse, which can subsequently be used to develop precise control strategies that could lead to more uniform conditions throughout the entire cultivation area and better control of crop needs. In this way, uniform quantity and quality of produce can be achieved, while the risk of diseases at specific problematic regions of the greenhouse could be minimized. Analysis based on WSN measurements during summer and winter periods showed significant spatial variability in temperature and humidity, but also in transpiration and conditions that favour condensation on leaves surface.

Keywords: wireless sensor networks, climate variability, plant-based measurements, precision greenhouse horticulture

INTRODUCTION

Climate control in greenhouses can be a highly complicated task, since many, strongly coupled factors are affecting the inside environmental conditions and the final decisions concerning the control regimes. In addition, spatial heterogeneity is inherent to the biological and physical aspects of agricultural systems. In modern greenhouses, several measurement points at plant level are required to create an objective and detailed view of the climate at various regions around the covered space. Specific climatic gradients can cause significant differences in terms of yield, productivity, quantitative and qualitative characteristics of the plants, as well as the development of various diseases. To be able to eliminate these differences, a precise and accurate distributed monitoring system is required.

With the relatively recent advancement of wireless sensor networks (WSNs), such a distributed monitoring is technically and economically feasible. These networks usually consist of cheap, battery-powered nodes, equipped with specific sensors that collect appropriate information and transmit it wirelessly to a central base-station, which stores the received data for future processing or uses it dynamically for monitoring, control or other purposes (Akyildiz et al., 2002).

Kittas and Bartzanas (2007) have reported that many researchers in greenhouse environment have considered the climate inside a greenhouse as uniform. However, several studies have investigated the heterogeneity of greenhouse conditions (e.g. Soni et al., 2005;

---

[a] E-mail: nkatsoul@uth.gr

Teitel et al., 2010). With the capability of multiple measuring points that the WSN technology provides, the exploitation of these findings is now feasible. Several recent works have investigated the use of WSNs for the estimation of climatic variability in the greenhouse (Castillo, 2007; Bojaca et al., 2009; Balendock et al., 2014). In addition, efforts have been made to introduce such analyses in the development of distributed greenhouse environmental control (Gonda & Cugnasca, 2006; Pawlowski et al., 2009; Chaudhary et al., 2011).

In this work, the primary goal was to detect and analyse the spatial variability of temperature and relative humidity conditions inside a commercial greenhouse and, based on that, to potentially investigate the possibility of detecting problematic situations for the cultivated plants, thus making feasible the development of environmental control methodologies that can reduce their occurrence.

MATERIALS AND METHODS

The experiments were conducted in a commercial greenhouses in Pirgetos, in 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 by 48 m). It is equipped with a wet pad / fans system located along the long side wall of the greenhouse; roof windows, a heating system with floor and grow heating pipes and recirculating air fans located 4 m above ground. Each span has a separate operating zone of the heating and irrigation system. During the experiments, cucumber plants were cultivated in a hydroponic system on rockwool. The crop lines 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 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 Figure 1.

The experiments were conducted during two different periods: i) a "winter period" from February 12 to March 18 and ii) a "summer period" from May 1 to July 17. Measurements were sent to the WSN base-station every 2 minutes and then averaged over 10-minute intervals. It should be noted that some periods of problematic operation of the WSN existed during the experiments, producing sparse gaps in the registered measurements that ranged in duration, from several minutes to entire days. The reasons for the failure of the WSN will be checked and the correlations of nodes' signal strength with crop LAI and air relative humidity values will be analysed. Thus, there were some time 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:

$$MRD = \frac{\sum_{i=1}^{N} |V_i - V_m|}{N \cdot V_m} \tag{1}$$

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 smaller 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 penalized least squares method (Garcia, 2010).

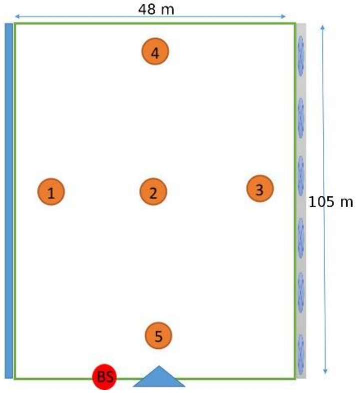

Figure 1. WSN nodes layout inside the greenhouse. Wet-pad on the left side (West) and fans on the right side (East). Greenhouse entrance and WSN base-station on the bottom side (South).

RESULTS AND DISCUSSION

Temperature and relative humidity spatial variability

Based on the estimated metrics of spatial uniformity of temperature measurements (Table 1), it seems that the largest heterogeneity takes place 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 0.0361). These differences in temperature values could 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 the air flow was crosswise to the crop lines, since even for the case of air flow parallel to crop lines, other authors observed similar or even higher air temperature differences (e.g. see Kittas et al., 2003; Lopez et al., 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 occurs during daytime for both periods (maximum differences around 9%, standard deviation of average humidity values between the 5 sensors around 3 to 3.7%, and MRD values around 0.033). Although the air temperature variations seem 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 night time, relative humidity measurements were quite uniform during both experimental periods (summer and winter). It has to be noted that during the nigh time, the air recirculating fans were used, something that seems to have resulted in higher microclimate homogeneity.

The contour plots in Figures 2 and 3 give a schematic representation of the observed variations for temperature and relative humidity, respectively. 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 for each period (season), for both temperature and humidity.

Figure 4 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 distinction between daytime and night time, rather than between summer and winter periods.

Table 1. Average temperature values and standard deviations (ºC) of each sensor for daytime and night time periods. Also, the maximum average difference, the standard deviation of the averages, and the MRD of the averages are included. Sensors position are indicated by x-y coordinates: x indicates the greenhouse length and y indicates the greenhouse width.

	Summer				**Winter**			
	Day		**Night**		**Day**		**Night**	
Sensor number and (x-y) coordinates	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Std**
Sensor 1 (55-5)	23.4	4.83	17.3	3.21	20.8	5.11	16.0	1.24
Sensor 2 (55-24)	24.8	5.13	18.0	3.17	21.6	5.90	16.2	1.20
Sensor 3 (55-44)	25.6	5.04	18.7	3.34	21.0	5.69	15.5	1.47
Sensor 4 (95-24)	26.7	5.73	18.0	3.40	21.9	6.28	16.7	1.27
Sensor 5 (10-24)	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	0.0361		0.0216		0.0170		0.0194	

Table 2. Average relative humidity values and standard deviations (%) of each sensor for daytime and night time periods. Also, the maximum average difference, the standard deviation of the averages, and the MRD of the averages are included. Sensors position are indicated by x-y coordinates: x indicates the greenhouse length and y indicates the greenhouse width.

	Summer				**Winter**			
	Day		**Night**		**Day**		**Night**	
Sensor number and (x-y) coordinates	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Std**	**Mean**	**Std**
Sensor 1 (55-5)	74.6	11.89	77.3	8.57	64.0	15.32	57.4	15.52
Sensor 2 (55-24)	78.6	11.95	80.3	7.99	65.5	17.32	60.5	16.98
Sensor 3 (55-44)	78.5	13.66	80.8	8.70	64.2	17.86	59.6	16.52
Sensor 4 (95-24)	69.6	13.49	78.9	8.61	68.6	15.91	60.1	16.94
Sensor 5 (10-24)	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	0.0345		0.0202		0.0321		0.0246	

Transpiration variability

Crop transpiration is an important parameter that can be used to optimize irrigation scheduling towards the increase of water use efficiency and subsequently, 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) at the measuring points, based on the following equation:

$$Tr = a\,R + b\,\mathrm{VPD} \qquad (2)$$

where, R is the radiation intensity (W m^{-2}) (measured in the centre of the greenhouse), and 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).

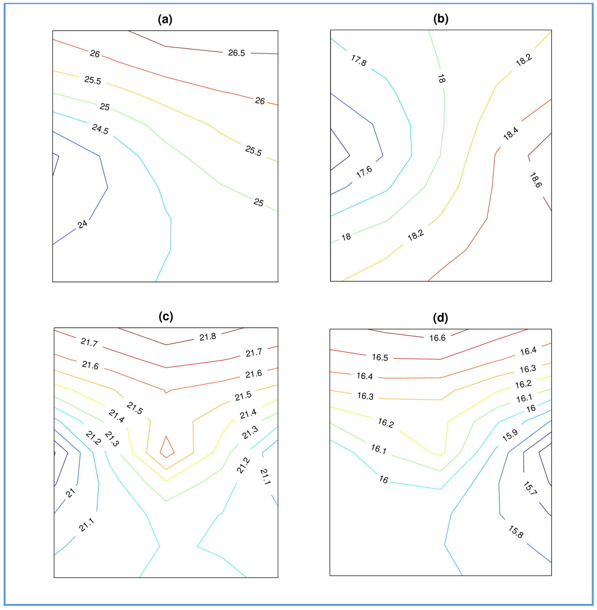

Figure 2. Contour plots of avg temperature. (a) Summer period – daytime, (b) Summer period – night time, (c) Winter period – daytime, (d) Winter period – night time.

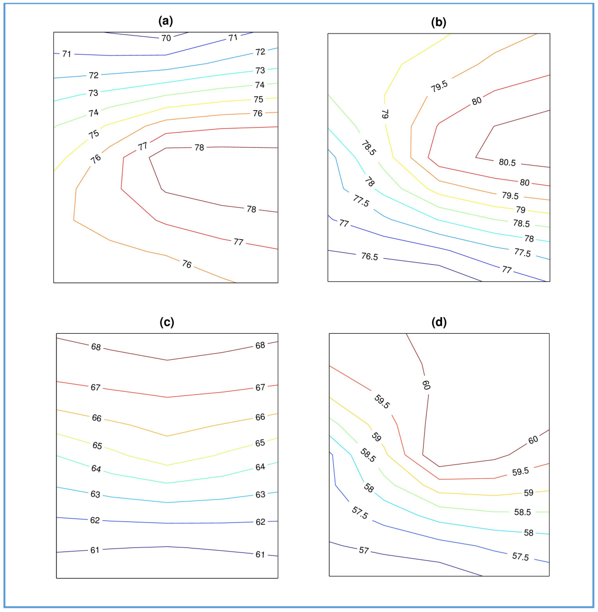

Figure 3. Contour plots of avg rel. humidity. (a) Summer period – daytime, (b) Summer period – night time, (c) Winter period – daytime, (d) Winter period – night time.

Each rectangular corresponds to the greenhouse layout of Figure 1 (up is North side, bottom is South side), and contour lines represent the average values, based on WSN measurements at the position of the nodes and interpolated values for the rest of the greenhouse area.

Figure 5 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 (Figure 5c) is similar to that during daytime. 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 6 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). 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. They incorporated subroutines into the CFD code which computed the crop dynamical response as a function of local conditions. Their model found a strong heterogeneity in the indoor environment, which was characterised by a main air stream crossing from wind- ward to leeward openings, while the air along the floor and walls remained stagnant. Furthermore, the model computed the level of crop transpiration on the north side to be 30% smaller than other locations because of lower solar energy and air speed. Similar results were also observed by Fatnassi et al. (2006) who simulated crop transpiration in a multispan greenhouse.

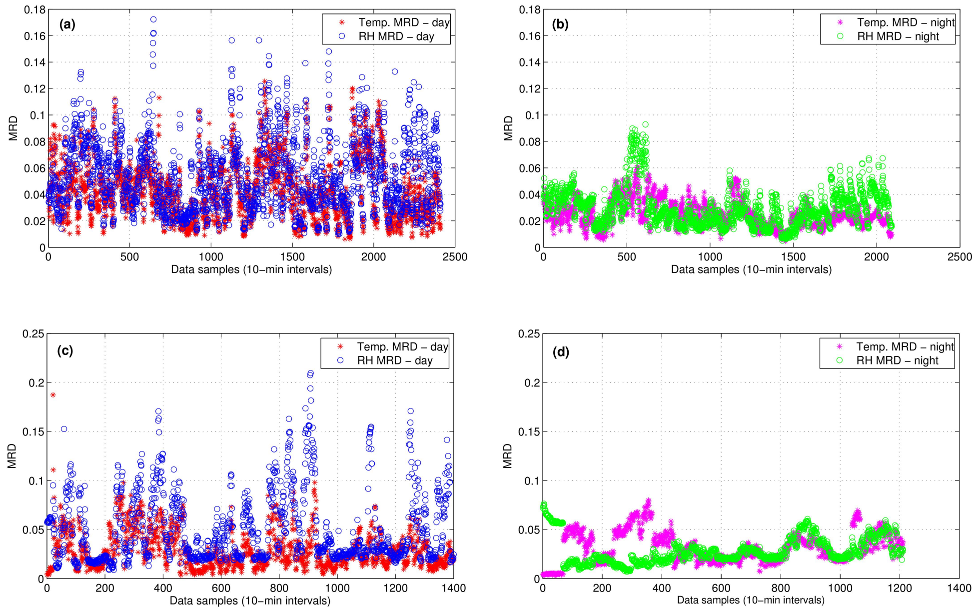

Figure 4. MRD of temperature and relative humidity values, during summer ((a) and (b)) and winter ((c) and (d)) periods, for both daytime ((a) and (c)) and night time ((b) and (d)) periods.

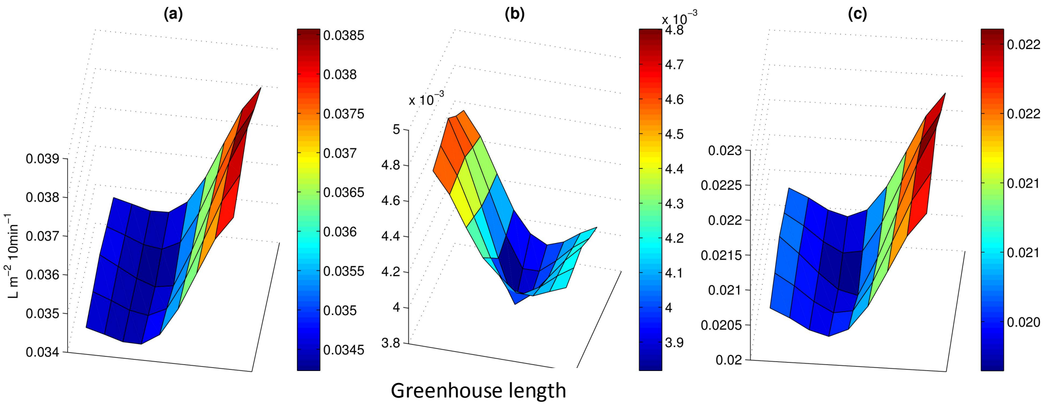

Figure 5. 3D surface plots of average transpiration during (a) daytime, (b) night time, and (c) on average during the entire summer period. Left side is North, right side is South.

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 3 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 overall longer periods of condensation conditions that occurred during the winter period, and their different spatial distribution (Figure 7b), make the overall (average) frequency distribution being quite different, with larger variability along the long side of the greenhouse (Figure 7c), with the area close to the entrance of the greenhouse having, in general, less than half time of condensation conditions compared to the other side of the greenhouse.

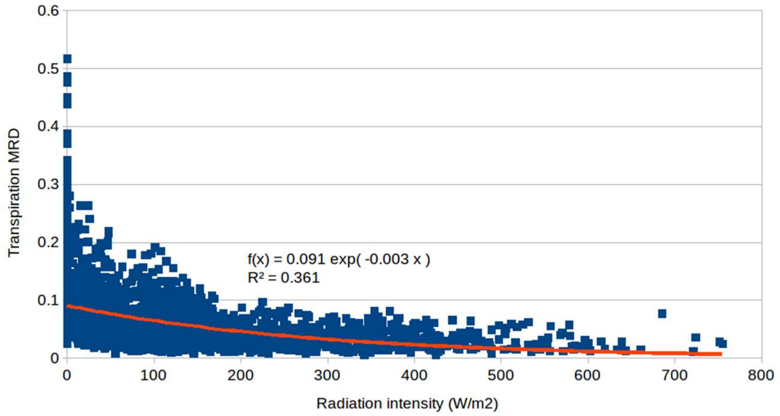

Figure 6. MRD of transpiration correlation with radiation intensity.

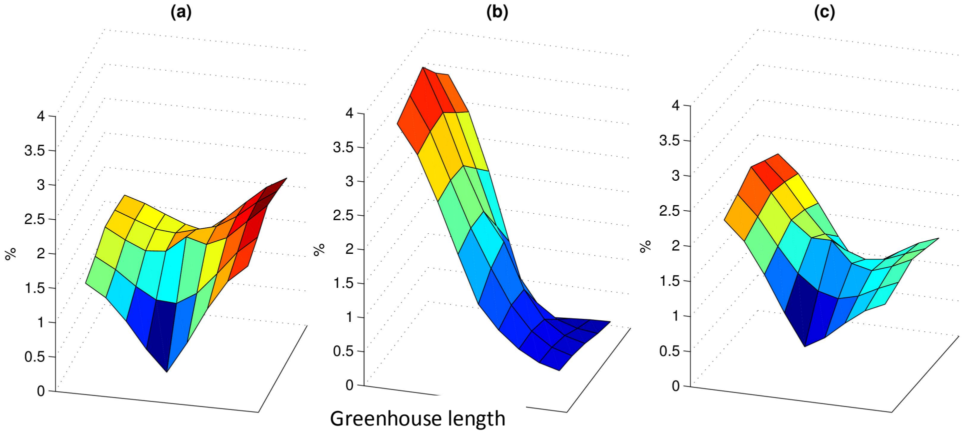

Figure 7. 3D representation of time percentages of condensation conditions on the plant leaves in the greenhouse layout: (a) during the summer period, (b) during the winter period, (c) on average during the entire experiment. Left side is North, right side is South.

CONCLUSIONS

Spatial heterogeneity of the environmental conditions inside a commercial greenhouse was investigated, 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 also analysed in order to examine the possibility of applying precise irrigation control that could reduce water consumption. It was found that transpiration levels varied evenly along the long side of the greenhouse, making the development of such precise irrigation control systems feasible. Finally, the frequency of occurrence of conditions that favoured condensation on the leaves of the plants was investigated, by using the leaf temperature measurements. It was found that there were areas in the greenhouse with up to 36 times greater frequency of occurrence of such conditions than others, with the greatest diversity happening during the winter period.

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 minimizing the risk of diseases at specific problematic regions of the greenhouse and efficiently reducing irrigation water consumption. As a future work, the design and development of such systems will be investigated, based on even more dense WSNs.

ACKNOWLEDGEMENTS

This work was funded by the Greek GSRT Research Excellence Grant (ΑΡΙΣΤΕΙΑ) project “GreenSense”.

Literature Cited

Akyildiz, I.F., Su, W., Sankarasubramaniam, Y., and Cayirci, E. (2002). Wireless sensor networks: a survey. Comp. Netw. *38*, 393–422.

Balendock, J., Sapounas, A.A., Kempkes, F., Van Os, E.A., Van der Schoor, R., Van Tuijl, B.A.J., and Keizer, L.C.P. (2014). Using a wireless sensor network to determine climate heterogeneity of greenhouse environment. Acta Hortic. *1037*, 539-546.

Bojaca, C.R., Gil, R., and Cooman, A. (2009). Use of geostatistical and crop growth modelling to assess the variability of greenhouse tomato yield caused by spatial temperature variations. Comp. & Elec. Agr., *65*, 219-227.

Boulard, T., Wang, S. (2002). Experimental and numerical studies on the heterogeneity of crop transpiration in a plastic tunnel. Comp. Electr. Agric. *34*, 173–190.

Castillo, C. (2007). Implementation of a prototype wireless sensors network for greenhouses. PhD Thesis, UPN-Quito, Ecuador.

Chaudhary, J.C., Nayse, S.P., and Waghmare, L.M. (2011). Application of wireless sensor networks for greenhouse parameter control in precision agriculture. Int. J. of Wireless & Mob. Net., *3*, 140-149.

Fatnassi, H., Boulard, T., Poncet, C., Chave, M., 2006. Optimisation of greenhouse insect screening with computational fluid dynamics. Bios. Eng., *93*, 301–312.

Garcia, D. (2010). Robust smoothing of gridded data in one and higher dimensions with missing values. Comp. Stat. & Data An., *54*, 1167-1178.

Gonda, L, and Cugnasca, C.E. (2006). A proposal of greenhouse control using wireless sensor networks. Proc. 4th World Congr. on Comp. in Agr. & Nat. Res., Orlando, FL, USA.

Katsoulas, N., Kittas, C. (2011). Greenhouse crop transpiration modeling. In (Gerosa, G., Ed.): Evapotranspiration - from measurements to agricultural and environmental applications, ISBN: 978-953-307-512-9, InTech.

Kittas, C., and Bartzanas, T. (2007). Greenhouse microclimate and effectiveness under different ventilator configurations. Build. Environ. *42*, 3774-3784.

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

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. Bios. Eng., *113*, 334-350.

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

Soni, P., Salokhe, V.M., and Tantau, H.J. (2005). Effect of screen mesh size on vertical temperature distribution in naturally ventilated tropical greenhouses. Bios. Eng., 92, 469-482.

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