DETERMINATION OF SENSOR LOCATIONS FOR MONITORING OF GREENHOUSE AMBIENT ENVIRONMENT

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ABSTRACT

In protected crop production facilities such as greenhouse and plant factory, farmers should be present and/or visit frequently to the production site for maintaining optimum environmental conditions and better production, which is time and labour consuming. Monitoring of environmental condition is highly important for optimum control of the conditions, and the condition is not uniform within the facility. Objectives of the paper were to investigate spatial and vertical variability in ambient environmental variables and to determine optimum sensor locations. Experiments were conducted in a strawberry-growing greenhouse (greenhouse 1) and a cherry tomato-growing greenhouse (greenhouse 2). Selected ambient environmental variables for experiment in greenhouse 1 were air temperature and humidity, and in greenhouse 2 were air temperature, humidity, luminous intensity, and CO_2 concentrations. Variability in air temperature and humidity at noon was the highest, and reduced over time. Locations of measured maximum and minimum values were changed by window-opening and heating operation. Scenarios for the location of luminous intensity and CO_2 concentration sensors in greenhouse were suggested considering the variability, and also control methods.

Keywords: Greenhouse, Ambient environment, Monitoring, Variability, Sensor location

INTRODUCTION

Protected crop production has advantages of stable and year-round production, and also controllable quality and yield. Ambient environmental factors affect crop growth and quality. Adams et al. (2001) compared tomato yield grown in four different temperatures of 14, 18, 22, and 26°C for a 27-week growing season. Corresponding tomato weights were 18.3, 57.7, 51.3 and 23.9 g, respectively. Mortensen and Gislerod (2005) compared growth of the six-cut rose cultivar grown in 75% and 90% relative humidity (RH) levels, and found that 71% and 27% of the flowers opened, respectively. The mildew was not detected in 90% RH and only minor infections were observed in 75% RH. Hirama et al. (2006) compared four species of cucumber growth in different temperature and relative humidity (RH) conditions of 29°C, 70% RH and 25°C, 55% RH. Days until harvesting were 0.7~2.6 days shorter in the growing conditions with 29°C, 70% RH than with 25°C, 55% RH. Klaring et al. (2007) reported that CO_2 supply of about 500 g/m^2 using a control system in a greenhouse increased cucumber production by 37% compared with the greenhouse without additional CO_2 supply.

Farmers should be present and/or visit frequently to the production site to monitor, control, and maintain optimum environmental conditions. Recently, remote monitoring and control of the environmental conditions using internet or mobile devices have been reported and commercialized. For example, He et al. (2007) used code division multiple access (CDMA) wireless communication for web-based monitoring of temperature, RH, soil temperature, light intensity, and 4 images of an experimental maize field. Hwang et al. (2010) reported an environmental monitoring and control system for paprika greenhouse using sensor nodes with 2.4-GHz RF chips. Temperature, humidity, leaf temperature, leaf humidity were monitored and the real-time changes in growth was captured by CCTV. The developed system was tested through experiments using a test bed system and was installed in the paprika greenhouse.

Proper implementation and utilization of sensor technology are the most essential requirements for accurate monitoring the environmental factors in the protected crop production. Environment variables may show variability by location, direction, size and type of sensors, crops type, seeding rates, season and time. Therefore, investigation of the variations is prerequisite to the accurate monitoring. Zhao et al. (2001) reported temperature difference between at the top and bottom of crop canopy, using 10 temperature sensors installed at different heights. In a pepper greenhouse with a total area about 960 m^2, the temperature difference was about 5°C in July when the crop height was about 2.7 m.

Variations in environmental variables would be dependent on ventilation methods. Soni et al. (2005) found a vertical temperature difference caused by natural ventilation in four tomato-growing greenhouses of two plant growth stages (young and mature) during mid-April to late June. The highest temperature was measured near the roof, and temperature difference between the roof and coolest point was 5°C. Temperature gradients of maturing stages were 14% higher than those of younger plant stages. Li and Willits (2008) studied vertical variations of air temperature and humidity in a 6.7 × 12.1 m^2 fan-ventilated sweet pepper

greenhouse. When measured at five heights (0.46, 0.94, 1.40, 1.84, and 2.32 m) on the ridge and bone, vertical deviations of air temperature and humidity were 1.8°C, 10% with crops and 11.5°C, 12% without crops. The highest temperatures were predicted at the top of the canopies, and suggested that placing the sensor in the below the top of the canopy might be appropriate. Bojaca et al. (2009) compared variations of the temperature obtained at 30 points in a normal single-layer polyethylene greenhouse (PGH, 5100 m^2) and 35 points in a single-layer polyethylene greenhouse with automated roof ventilation (RPGH, 9792 m^2). The difference between the maximum and minimum air temperatures were 3.2°C in PGH and 4.1°C in RPGH. Temperature of the greenhouse with automated roof ventilation resulted in greater variation. It was pointed out that measuring with only one sensor near the center of the greenhouse would overestimate the average temperature of the entire area.

Tadj et al. (2010) investigated distribution of temperature and humidity in greenhouse by different heating methods. The experiments were performed in a tomato growing greenhouse of 8×20 m^2 size in where the heating pipes at the bottom and a heater at the upper were used for heating. In order to compare air velocity, air temperature, and RH by height, measured were obtained five heights (0.8, 1.0, 1.5, 2, 2.5 m) and 42 points and 21 points at 1 and 1.5 m heights. When heating pipes were used, temperature at the bottom of the greenhouse was the highest as 19°C and humidity of near the crops was the highest as 7%. When a heater was used, temperature at the upper of the greenhouse was the highest as 26°C and humidity at the bottom was the highest as 14%.

For optimum monitoring and control of environmental variables in a greenhouse, installation of sensors based on the variability would be preferable. Objectives of the paper were 1) to measure spatial and vertical variability in major ambient environmental variables in greenhouses, and 2) to develop scenarios of sensor locations suitable for remote monitoring of the variables.

MATERIALS AND METHODS

Sensors and wireless communication devices

Table 1 shows the selected ambient environmental variables (air temperature, air humidity, luminous intensity, and CO_2 concentrations) and specifications of the sensors. Air temperature and air humidity were measured using temperature/humidity sensors (CIPCAP-L Sensor; General Electric Company Co. Inc., Niskayuna, NY, USA). CIPCAP-L sensor measured using Integral PTAT (Proportional to Absolute Temperature) silicon transistor for temperature and capacitive polymer sensing technology for humidity. Luminous intensity was measured by a light sensor (PAR Light Sensor # 36681; Spectrum Technologies Inc., Plainfield, IL, USA) and CO_2 was obtained with a NDIR (Non-dispersive Infrared) sensor (SH-300STH Sensor; SOHA TECH Co. Ltd., Nowon-gu, Seoul, Korea). A wireless communication device (ZP24D-250RM-SR; B&B Electronics Co. Inc., Dayton, OH, USA) 2.4 GHz band with Zigbee protocol and Modbus protocol was selected in the study. Measurement data were

transferred to a PC using a single receiver and seven transmitters. The maximum communication distance between the two wireless communication devices was about 90 m.

Table 1. Selected environmental variables and specifications the sensors.

Variable	Temperature	Humidity	Luminous intensity	CO_2 concentrations
Model	CIPCAP-L	CIPCAP-L	PAR Light Sensor	SH-300STH
Range	-55~150°C	0~100%	0~2,500 $\mu Mol/m^2 s$	0~3,000 ppm
Accuracy	±0.6°C	±2%	±5%	±2%

Experimental methods

Characterization of the sensors

Commercial sensors may not provide the same output even in the same environment. To verify the output from the sensor, output values from temperature/humidity sensors were compared at three different places: temperatures of 25, 15, 20°C and RH values of 55, 60, 70%, respectively. During the measurement, air flow was blocked to prevent the change of temperature and humidity. Measurements were obtained for 1 minute with 3 replications at each condition.

In order to measure the accurate distribution of ambient environment variables in the greenhouse, sensors should be stabilized in the changed condition. Based on the manufacturers' manuals, response time of the light sensor was less than one minute, and the CO_2 sensor less than 30 seconds. Temperature and humidity sensors take measurements in the state of heat balance by contact with objects, and contact sensors systematically would have some delay time (Kim and Kim, 2002). To determine response time of the temperature and humidity sensors, a temperature & humidity chamber (HB-105SG; Hanbaek Co. Ltd., Bucheon, Gyenggi-do, Korea; Table 2) was used. Temperature/humidity sensors were first stabilized in temperature of 24±1°C and humidity of 40±1.5%, then inside of the chamber. Temperature and RH settings of the chamber 30, 40, 50, 60, 70, and 80°C at RH of 40%, and 50, 60, 70, and 80% at temperature of 24°C. All measurements were repeated three times.

Table 2. Specifications of the temperature & humidity chamber.

Items	Specifications
Temperature range	- 20 ~ 120°C
Humidity range	30 ~ 98%
Temperature accuracy	± 0.1°C at 37°C
Humidity accuracy	± 2% at 70%

Experimental greenhouses

Field experiments were conducted in two greenhouses in winter (December 2011 and January 2012, Korea): strawberry-growing (Greenhouse 1) and cherry tomato-growing (Greenhouse 2) facilities. Dimensions of the greenhouse 1 (L, W,

and H) were 100, 6.5 and 2.5 m, the structure consisted of three layers (Figure 1). Both sides of greenhouse 1 could be open with window opening motors, and an irrigation system was installed. Strawberries were planted before three weeks, and harvesting started one week after that.

Experiments were conducted from noon when the highest temperature was expected to sunset when the greatest environmental change was expected, at two-hour intervals (12:00, 14:00, 16:00, and 18:00). Following farmers' practice, the right side window was open at 12:00 and both windows were closed at other times. Measurement was started after 1-minute stabilization period at each location, but all measurements at each experiment was done less than 30 minutes to minimize changes in the environmental conditions. Measurements were obtained at 0 and 0.5 m heights at the sides and up to 1 m in the middle of the greenhouse, and 49 spatial locations over half or quarter of the area, assuming spatial symmetry of the environmental conditions (Figure 2).
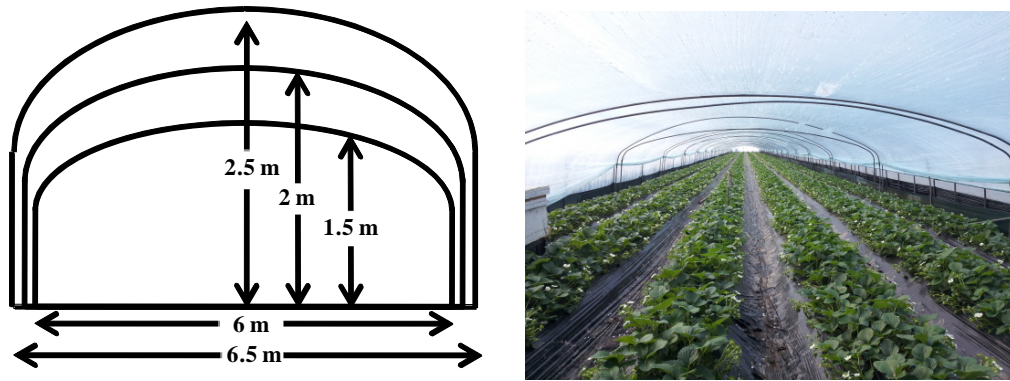

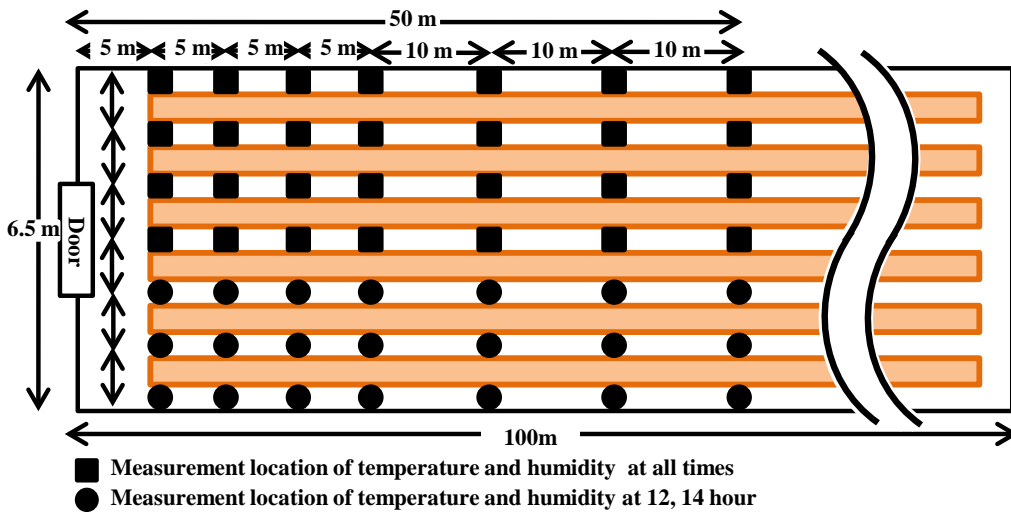**Figure 1.** Dimensions (left) and view (right) of Greenhouse 1.

Figure 2. Measurement locations of temperature and humidity in Greenhouse 1.

Dimensions of the cherry tomato greenhouse (L, W, and H) were 25, 7.5, and 4 m, and the structure consisted of 2 layers (Figure 3). Experiments were

conducted on 25th January, 2012. Both sides could be open, an irrigation system using 4-line drip pipes was installed, and the temperature could be controlled at 17°C by a tunnel-type heater. Cherry tomato was planted two weeks before, and tomato canopy height was about 30 cm.

Durations of sensor stabilization and measurement were similar as in greenhouse 1. Experiments were performed at noon (12:00~14:00) and sunset (17:00~19:00). Measurement locations of temperature, humidity, luminous intensity, and CO_2 concentration were illustrated in Figure 4. At each experiment, measurements were taken by window opening and heater operation: windows open, right window open, windows closed, window closed and heater operation. After the window and heater operation, 5-minute stabilization period was considered. Measurement heights were 0, 1, 2, and 3 m in the middle and limited to 2 m at the side, and data were taken at 126 locations at each height for temperature and RH. Luminous intensity and CO_2 concentration were measured at 10 points and 14 points at the middle of the greenhouse (Figure 4).
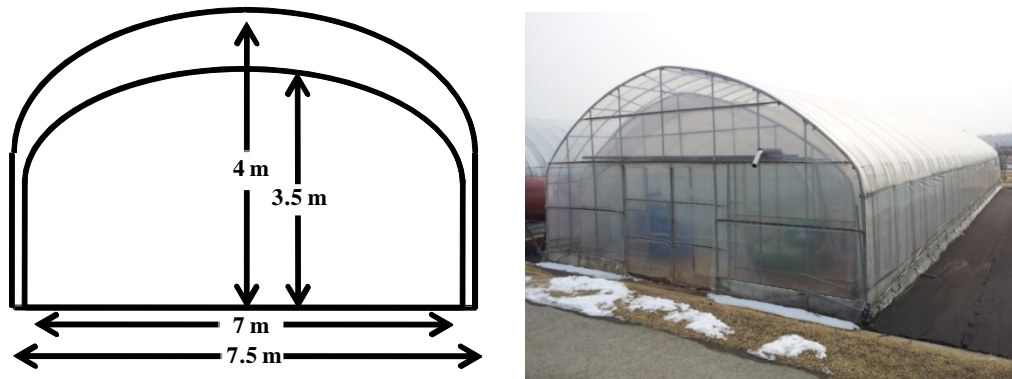

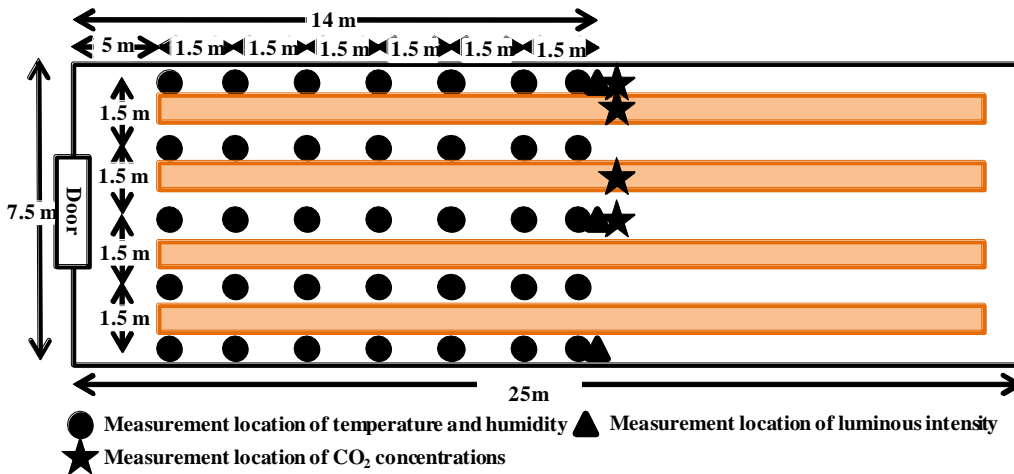**Figure 3.** Dimensions (left) and view (right) of Greenhouse 1.

Figure 4. Measurement locations of the environmental variables in Greenhouse 2.

RESULTS AND DISSCUSION

Characteristics of the temperature and RH sensors

Results of calibration tests for the temperature and RH sensors were summarized in Tables 3 and 4. Temperature sensors provided the same outputs, while one of the RH sensors gave greater values than others by 1.5%. The deviation was considered in later experiments.

Table 3. Results of calibration tests for the temperature sensors.

Sensor No.	No.1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
1st Avg. (°C)	25.20	25.13	25.03	25.15	25.14	25.20	25.20
1st Std. Dev.	0.00	0.17	0.23	0.15	0.16	0.00	0.00
2nd Avg. (°C)	14.89	15.07	15.00	14.87	15.05	15.07	15.07
2nd Std. Dev.	0.11	0.00	0.11	0.10	0.07	0.00	0.00
3rd Avg. (°C)	20.31	20.61	20.53	20.14	20.06	20.05	20.31
3rd Std. Dev.	0.00	0.24	0.24	0.24	0.25	0.25	0.00
Duncan's result group	A	A	A	A	A	A	A

Table 4. Results of calibration tests for the relative humidity sensors.

Sensor No.	No.1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
1st Avg. (%)	55.11	54.94	56.47	55.02	54.96	54.93	55.01
1st Std. Dev.	0.00	0.11	0.11	0.12	0.12	0.11	0.12
2nd Avg. (%)	60.32	60.32	61.53	60.24	60.14	60.04	60.37
2nd Std. Dev.	0.22	0.22	0.19	0.16	0.13	0.19	0.24
3rd Avg. (%)	70.21	70.02	71.46	70.10	70.98	70.06	70.24
3rd Std. Dev.	0.12	0.24	0.18	0.23	0.17	0.29	0.17
Duncan's result group	A	A	B	A	A	A	A

Response time due to changes in temperature and RH was shown in Figure 5. Generally, response to decrease was slower than that to increase in those factors. Within the experimental range, response time was 42 seconds for 6.35°C increase, and 169 seconds for 53.55°C increase. Average response time for 1°C increase was about 4 seconds. Similarly, average response time 1°C decrease was about 12 seconds. In case of RH, response times for 41.34% increase and 41.50% decrease were 90 and 272 seconds, respectively. Average response times for 1% increase and 1% decrease were 3 and 7 seconds, respectively.
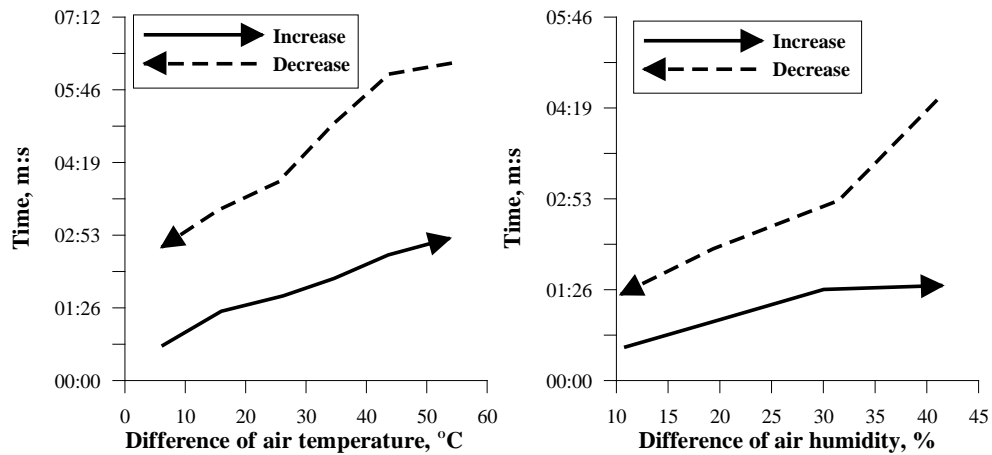
Figure 5. Response time of the temperature and RH sensors.

## Variability of environmental variables in greenhouses

Greenhouse 1

Tables 5 and 6 show overall variability of temperature and RH in greenhouse 1 during the experiments. Average temperature increased from 13.62°C at 12:00 to 17.68°C at 14:00 and decreased after that, while RH increased continuously until 18:00. In the experiment at 12:00 when the right window was open, the maximum air temperature of 17.20°C was measured at the left middle location at a 0-m height, and the minimum temperature of 11.00°C was measured at the right front location at a 0.5-m height. RH was the highest (78.76%) at the left window part at a 0-m height, and the lowest (59.49%) at the right window part at a 0-m height. When both windows were closed (14:00), the maximum (19.30°C) and minimum (15.70°C) temperatures were obtained at the center at a 0.5-m height and near the entrance at a 0-m height, respectively. RH was the lowest (74.21%) at the entrance at a 0-m height, and the highest (84.65%) at the center at a 1-m height. Differences between the maximum and minimum temperature and RH values were greater when one side of the windows were open than when both windows were closed. Figure 6 shows spatial distribution of air temperature and RH at a 0.5-m height. Temperature and RH values were low at the right side due to ventilation at 12:00, while low at both sides and high at the center at 14:00.

Table 5. Variability of the measured air temperature in greenhouse 1. (Unit: °C)

Time	Average	Maximum	Minimum	Range	Std. Dev.
12:00	13.62	17.20	11.00	6.20	1.32
14:00	17.68	19.30	15.70	3.60	0.86
16:00	14.03	15.86	11.90	3.94	0.83
18:00	11.52	12.62	10.50	2.12	0.51

Table 6. Variability of the measured air RH in greenhouse 1.　　　(Unit: %)

Time	Average	Maximum	Minimum	Range	Std. Dev.
12:00	70.05	78.76	59.49	19.27	4.35
14:00	80.18	84.65	74.21	10.44	2.66
16:00	85.67	93.58	78.91	14.67	2.88
18:00	93.18	97.56	86.38	11.18	2.27
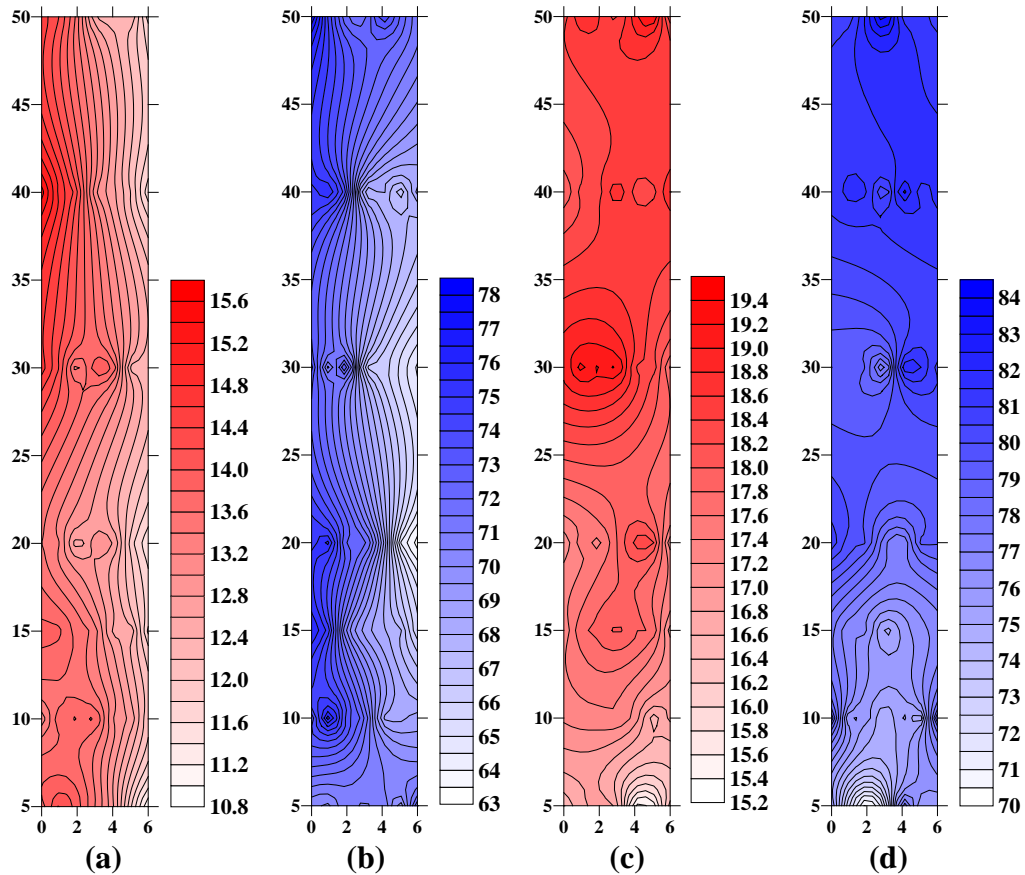
Figure 6. Spatial distribution of air temperature and humidity at a 0.5-m height in greenhouse 1: (a) air temperature and (b) RH with the right side window open at 12:00, (c) air temperature and (d) RH with both windows closed at 14:00.

Tables 7 and 8 show the overall variability of air temperature and RH at noon and sunset in greenhouse 2. Comparing resulted air temperature and humidity at noon and sunset, the differences in the average of air temperature and humidity were the highest as 3.23°C and 9.12% with both windows closed and the lowest as 0.50°C and 2.07% with both windows open. Differences between the maximum and minimum air temperatures at noon and sunset were the highest when both windows were open. At noon, the maximum and minimum air temperatures were measured near the front center at a 0-m height and at the left side at a 2-m height, respectively, and the difference was 3.47°C. At sunset, the maximum and minimum air temperatures were measured at the center at a 0-m

height and at the left side at a 1-m height, respectively, and the difference was 2.38°C.

Difference between the maximum and minimum RH at noon was the highest when both windows were open. The maximum and minimum RHs were measured at the left side at a 1-m height and near the center at a 0-m height, respectively, and the difference was 16.21%. At sunset, the greatest variability was observed when the heater was operated (11.25%).

Table 7. Variability of the measured air temperature in greenhouse 2. (Unit: °C)

Time		Average	Maximum	Minimum	Range	Std.Dev.
Noon	Both windows open	8.21	10.60	7.13	3.47	0.87
	Right window open	9.72	11.56	8.11	3.45	0.72
	Both windows closed	11.62	12.86	10.72	2.14	0.47
	After heater operation	17.35	18.94	15.70	3.24	0.92
Sunset	Both windows open	7.71	9.29	6.91	2.38	0.80
	Right window open	8.70	9.68	8.07	1.61	0.39
	Both windows closed	8.39	8.75	7.85	0.90	0.19
	After heater operation	14.74	15.47	13.28	2.19	0.64

Table 8. Variability of the measured air RH in greenhouse 2. (Unit: %)

Time		Average	Maximum	Minimum	Range	Std.Dev.
Noon	Both windows open	72.61	79.72	63.51	16.21	3.82
	Right window open	71.66	80.44	64.77	15.67	3.54
	Both windows closed	70.72	73.97	66.89	7.08	1.27
	After heater operation	56.45	65.08	51.04	14.04	4.11
Sunset	Both windows open	74.68	77.22	70.25	6.97	1.82
	Right window open	76.14	79.28	72.36	6.92	1.51
	Both windows closed	79.84	85.18	76.53	8.65	1.57
	After heater operation	60.07	66.28	55.03	11.25	2.89

Statistics of luminous intensity and CO_2 concentration were listed in Table 9, and vertical maps were shown in Figures 7 and 8, respectively. Average and standard deviation of luminous intensity were 1,633.20 and 17.07 $\mu mol/m^2 s$ at noon and 61.00 and 12.26 $\mu mol/m^2 s$ at sunset, respectively. The maximum values were observed at a 3-m, close to the lighting source, for both cases. Average and standard deviation of CO_2 concentration were 175.96 and 17.07 ppm at noon and 306.40 and 3.80 at sunset, respectively, and the highest values were observed in crop growing regions.

Table 9. Variability of the measured luminous intensity and CO_2 concentration in greenhouse 2.

Environment variable	Time	Average	Maximum	Minimum	Range	Std. Dev.
Luminous intensity (Unit: μmol/m^{2}s)	Noon	1633.20	1661.00	1610.00	50.00	17.07
	Sunset	61.00	90.00	50.00	40.00	12.26
CO_2 concentrations (Unit: ppm)	Noon	175.96	180.66	173.34	7.32	2.62
	Sunset	306.40	312.50	302.73	9.77	3.80
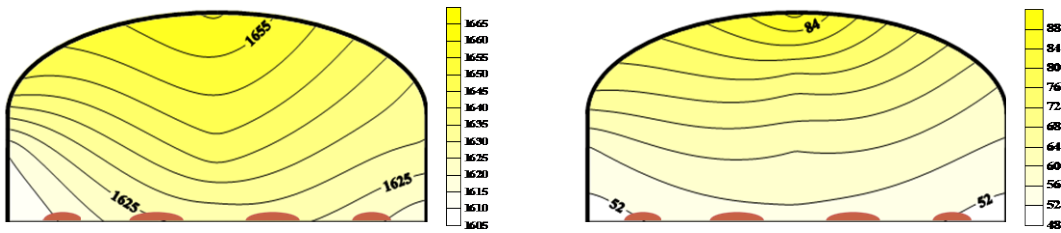
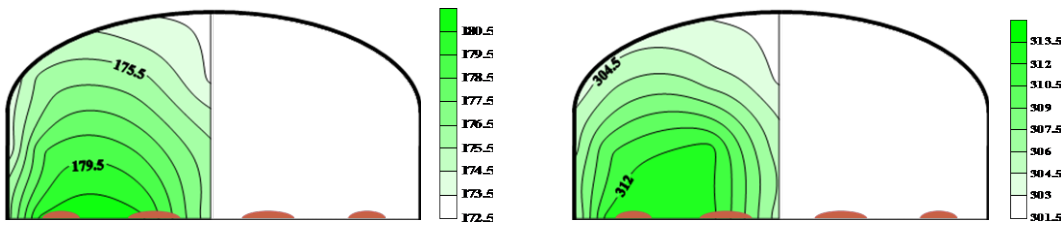**Figure 7.** Variability of luminous intensity at noon (left) and sunset (right).

Figure 8. Variability of CO_2 concentration at noon (left) and sunset (right).

Scenario of sensor location

Greater number of sensors would be better for monitoring environmental conditions when there were greater variability, but it would increase cost. As vertical location, the height near the crop canopy would be the best for luminous intensity and CO_2 concentration, and need to be variable as crop grows. For temperature and RH sensors, either close to the ground surface, half or height of crop canopy would be considered.

Determination of spatial locations of the sensors should consider variability (average, maximum, and minimum values), and also locations of components such as window, heater, and cooler. Candidates for sensor installation would be center, sides where windows and entrance gates are located. Criteria of sensor location would be also different. For example, lowest temperature would be important when heating is necessary during winter seasons, and highest temperature would be considered for cooling or ventilation operation.

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