Effects of humidity on tomato (*Lycopersicon Esculentum cv. Truss*) water uptake, yield, and dehumidification cost

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[1]Department of Agricultural and Biosystems Engineering, Macdonald Campus of McGill University, 21111 Lakeshore Road, Ste Anne de Bellevue, QC, Canada H9X 3V9; and[2]Département des Sols et de Génie Agroalimentaire, FSAA, Université Laval, Cité Universitaire, QC, Canada G1K 7P4. *Received 18 August 1998; accepted 22 May 1999.*

Trigui,M, Barrington,S.F. and Gauthier, L.1999. **Effects of humidity effect on tomato (*Lycopersicon Esculentum cv. Truss*) water uptake, yield, and dehumidification cost.** Can. Agric. Eng. 41:135-140. Air water-vapour pressure deficit is the prime factor controlling plant water uptake in greenhouses. In turn, plant water uptake affects several physiological processes such as pollination, plant growth, and fruit yield. In this study, plant water uptake and fruit yield were measured under four different ambient water-vapour pressure deficits (VPD). Four identical greenhouses were used to produce tomatoes under four different regimes of VPD. Greenhouses #1 and #2 were kept under a low and high VPD, respectively, while greenhouse #3 was kept under a low VPD during the day and a high VPD during the night. Greenhouse #4 was kept under a VPD dynamically controlled to maintain plant water uptake at 800 mL/plant per day. Plant water uptake and yield were highly correlated to ambient VPD as greenhouses #1 and #2 produced a low and high water uptake rate and yield, respectively. Greenhouse #3 produced an intermediate water uptake and yield, while greenhouse #4 lead to a water uptake and yield as high as that of greenhouse #2. Dehumidification costs were also highly correlated to VPD, as low VPD produced low water uptake requiring little dehumidification. Thus, managing plant water uptake can lead to a more efficient crop production.

Le déficit de pression de vapeur d'eau (DPV) est un des principaux facteurs affectant le contrôle de l'absorption d'eau par les plantes sous cultures abritées. Aussi, l'absorption d'eau affecte plusieurs fonctions physiologiques de la plante, tel la polinisation, la croissance et le développement des fruits. Dans le présent essai, on a mesuré le taux d'absorption d'eau et de rendements de plants de tomates gardés sous 4 différents régimes de DPV. Quatre serres identiques furent utilisées pour l'essai et chaque serre était maintenue sous un régime différent de DPV. Les serres 1 et 2, respectivement, étaient maintenues sous un faible et haut DPV alors que la serre 3 fut maintenue sous un rDPV faible pendant le jour et un DPV élevé pendant la nuit. La serre 4 fut maintenue sous un régime de DPV dynamique visant à maintenir le taux d'absorption d'eau de la plante à 800 mL plant^{-1} jour^{-1}. Le taux d'absorption d'eau et de rendement des plantes furent reliés de façon significative au DPV. Les serres 1 et 2 offraient des taux faibles et élevés, respectivement, alors que la serre 3 offrant un taux intermédiaire. Le coût énergétique de désumidificaiton était aussi relié de façon significative au DPV, puisqu'un faible déficit exigeait peu de frais de déshumidification. Par conséquent, la manipulation du DPV peut favoriser une transpiraiton plus efficace chez la plante et peut optimiser les rendements vis à vis les coûts de déshumidification.

INTRODUCTION

In Canada, the control of relative humidity (rh) is a key issue in greenhouse production, because it directly affects dehumidification cost, crop quality, and yield (Bakker et al. 1987; De Halleux and Gauthier 1995). During the winter, greenhouse air dehumidification is accomplished by diluting the ambient air with cold dry outside air, which in turn requires heating. The new greenhouse glazing materials are more airtight and heat efficient and require more dehumidification. Nevertheless, their air tightness provides a means of improving the control of the air relative humidity inside the greenhouse and, thus, plant water uptake.

The ideal range of relative humidity is generally defined between an upper and lower limit:

$$rh_{\min} < rh_{(t)} < rh_{\max} \qquad (1)$$

where rh $_{\min}$ and rh $_{\max}$ are the lower and upper limits of the ideal relative humidity, $rh_{(t)}$. The ranges of relative humidity which tend to optimize crop yield have been defined in terms of the vapour pressure deficit (VPD), a term referring to the difference between the saturated and the actual vapor pressure. VPD is the main factor controlling water uptake by the plant, because it determines water vapor differences between the plant roots and leaves and, thus, the water movement between these two points. Independent of temperature, VPD, expressed in kPa, predicts plant transpiration rate.

A VPD of 0.2 to 1.0 kPa was found to have little effect on the physiology and development of horticultural crops (Grange and Hand 1987). VPD levels of 0.5 to 0.7 kPa have been recommended (Bakker 1990). To avoid yield losses from small fruit size and the incidence of fungal diseases, VPD should be maintained above 0.5 kPa; but, to prevent losses in external fruit quality due to calyx withering, VPD should remain under 0.7 kPa. The proper pollination of tomato plants requires a VPD of 0.2 to 1.0 kPa (Piken 1984).

The upper and lower limits for greenhouse humidity should vary over time for optimum crop production. The VPD set point can be adjusted during the day, with solar radiation intensity to compensate for low solar radiation and the yield loss resulting from calcium deficiency (Aikman and Houter 1990). When solar radiation is low, plant transpiration is low,

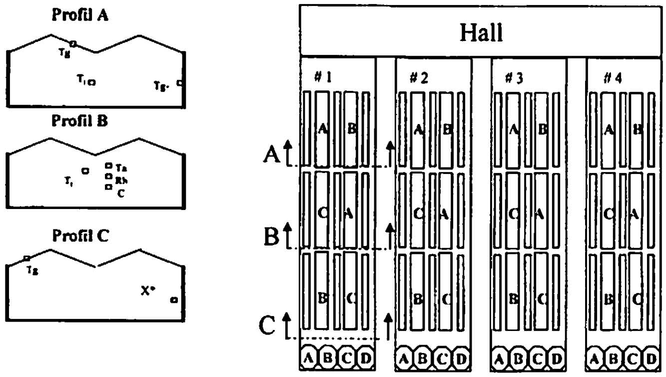

Fig. 1. The four experimental greenhouses and the monitoring systems. Tg, Tl, and Ta are the glazing, plant leaf, and air temperature sensor positions, Rh is the relative humidity sensor, C is the carbon dioxide sensor, and X is the computerized environmental control.

limiting its productivity. In such cases, low VPD leads to lower energy costs when yields are low. High solar radiation leads to excessive plant transpiration and calcium accumulation in the leaves rather than in the fruit. For each MJ m^{-2} d^{-1} reduction in incident radiation on the crop, below 8.7 MJ m^{-2} d^{-1}, the algorithm for VPD control should increase the set point by 0.04 kPa. As an alternative solution, the VPD set point can change continuously to ensure a minimum water uptake (Stangellini and van Meurs 1992) which can be estimated from the incoming global radiation (Stanghellini 1987).

A more cost-effective humidity control will be achieved with a better understanding of the effects of VPD on crop productivity and water uptake. The control of VPD should be coupled with criteria such as yield and dehumidification energy cost. The overall objective of this paper was to investigate the effects of VPD on water uptake and yield of tomatoes [*Lycopersicon esculentum cv. Truss*], and on associated heating and dehumidifying energy costs.

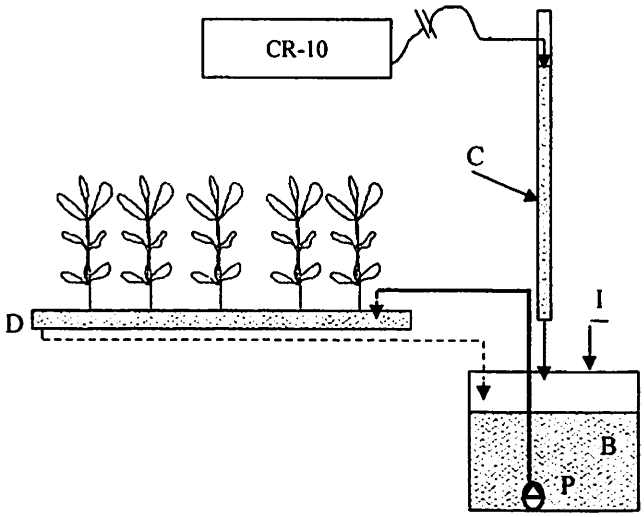

Fig. 2. The system measuring the plant transpiration rate. CR-10 is the hydroponic solution measuring device, C is the hydroponic solution column facilitating the measurement of plant water uptake, D is the hydroponic trough holding the tomato plants, B is the hydroponic basin, and P is the hydroponic solution pump.

METHODOLOGY

The experimental greenhouses

The experiment was conducted in four, free-standing, thermally-independent glass (Venlo type) greenhouses, 6.4 m in width by 24.0 m in length (Fig. 1), located on the Campus of Laval University (Québec City, QC). Single and double glass sheets glazed the greenhouse roof and wall, respectively. The greenhouses were equipped with supplemental lighting (high pressure sodium lamps) and thermal screens, systems for fogging, and CO$_2$ enrichment and a computerised climate control system. The day and night temperature set points were 20 and 18 °C, respectively. The injection system maintained the day and night CO$_2$ concentration at 800 and 350 ppm, respectively. All four greenhouses received the same radiation because of their identical structure and site. Humidity was controlled in the greenhouses by a fogging system. A heat pump dehumidified greenhouse #4, a positive pressure (mechanical) ventilation and a conventional heating system dehumidified greenhouse #2, while a natural ventilation and conventional heating system dehumidified greenhouses #1 and #3. The heat pump dehumidifying greenhouse #4 cooled the ambient air, condensed and removed its moisture, and returned the extracted heat to the greenhouse.

Each greenhouse housed 15 hydroponic troughs each holding 20 tomato plants. The tomato plants *[Lycopersicon esculentum cv. Truss*] were seeded on July 24, 1993 in rockwool cubes and transplanted into the hydroponic troughs after 6 weeks. The hydroponic nutrient solution was adjusted daily to maintain a constant salt concentration of 2.4 dS/m. Each tomato plant was trimmed to maintain 20 leaves per plant at all times. The experiment for testing the effect of VPD was conducted during the tomato plants production period, from November 1993 to May 1994.

Instrumentation

During the experiment, inside and outside climatic data were recorded using two data logger systems (Fig. 1), a CR-10 (Campbell Scientific, Logan, UT) and SCU (Landys & Gry, Buffalo Grove, IL), for counter verification. The following sensors were used :

1. relative humidity and air temperature with HMD 20 UB / Yb sensors (Vaisala sensors system, Woburn, MA);
2. CO$_2$ using sensors from Landys & Gry (Buffalo Grove, IL);
3. temperature of the vegetation, of the hydroponic solution, and of the glass glazing with type T thermocouples, and;
4. radiation with LI-COR-200 SB sensors (LI-COR, Lincoln, NE).

Inside the greenhouse, all temperature and relative humidity sensors were shielded from radiation and placed in a ventilated enclosure. Measurements were taken every minute, averaged over 15 min intervals, and transferred to a desktop computer for analysis.

Table I. Levels of vapour pressure deficit tested as treatments.

Green house	Nominal VPD (kPa)		Dehumidification system
	day	night	
#1	0.4	0.4	natural ventilation and heating
#2	0.8	0.8	mechanical venitlation and heating
#3	0.8	0.4	natural ventilation and heating
#4	dynamic control		heat pump

Note: In greenhouse #4, the VPD set point was continuously adjusted to maintain the transpiration rate at 800 mL plant^{-1} d^{-1}

Table II. Mean temperature and VPD for the experimental period.

Green house	Temperature (°C)			VPD (kPa)		
	day	night	daily	day	night	daily
#1	20.6 (0.12)	17.3 (0.23)	18.7 (0.42)	0.40 (0.03)	0.51 (0.03)	0.44 (0.02)
#2	19.5 (0.09)	17.2 (0.05)	18.1 (0.16)	0.81 (0.05)	0.84 (0.03)	0.82 (0.05)
#3	19.6 (0.10)	17.3 (0.02)	18.3 (0.03)	0.70 (0.05)	0.51 (0.03)	0.63 (0.05)
#4	20.3 (0.15)	17.3 (0.05)	18.5 (0.04)	0.75 (0.04)	0.71 (0.04)	0.73 (0.03)

The standard deviation is the value in parenthesis.

The relative humidity sensors were calibrated monthly with HMK 20 sensors (Vaisala Sensors system, Woburn, MA). The HMK 20 sensors were also calibrated using three salt solutions to create relative humidity levels of 11.4, 74.5, and 96.4%. Their reading error was 3%. The thermocouples were initially calibrated in water at 0 and 80°C. Their reading error was 0.5%. The radiation LI-COR- 200 SB sensors (LI-COR, Lincoln, NE) were calibrated using a LI-COR-1800 sensor.

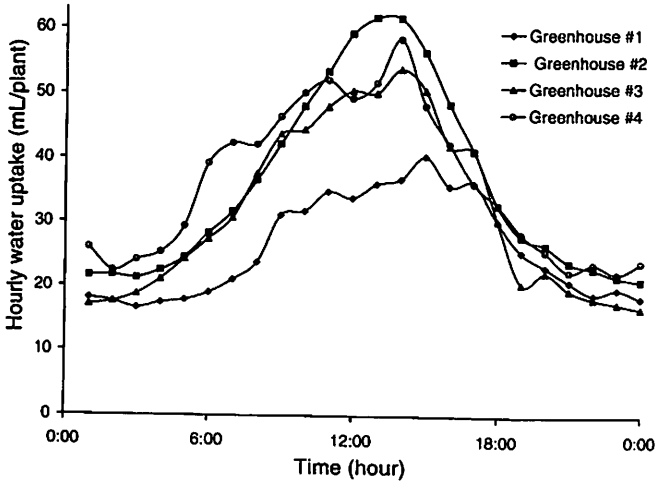

Fig. 3. Typical hourly water uptake over 24 hours.

Plant water uptake in each experimental trough was measured by monitoring the loss of hydroponic solution (Fig. 2). Each experimental trough was fed from a tub where the level of solution was maintained using a float. In turn, the tub was filled from a PVC (polyvinyl chloride) column, 15 mm in diameter by 1200 mm in height, where a CR-10 controller measured the quantity of liquid removed from the column.

Method

The effect of VPD on tomato yield and heating and dehumidifying energy costs was measured from November 1993 to May 1994. Each of the four greenhouses consisted of one treatment, managed under a different VPD regime (Table I). Low and high VPD were maintained in greenhouses #1 and #2, respectively. Greenhouse #3 was subjected to a high and a low VPD during the day and night, respectively. Greenhouse #4 was dynamically managed, and its VPD was varied to obtain a water uptake rate of 800 mL/plant per day (Table I). This rate was determined as the optimum water uptake level before the start of the experiment. Greenhouse air temperature and VPD set points were controlled by a computer system receiving ambient temperature and relative humidity readings. The system also adjusted the heating, ventilation, and dehumidification rates accordingly. Greenhouse temperature, relative humidity, and incoming radiation were continuously recorded in all four structures.

Only 6 of the 15 troughs in each greenhouse were selected for water uptake measurements (troughs A, B, and C, Fig. 1). The yield of each experimental trough was also measured using 5 plants selected at random at the beginning of the experiment. The fruits from each experimental plant were harvested and weighed twice a week throughout the experimental period.

In each greenhouse, the energy consumed was recorded. With all four greenhouses set at the same ambient air temperature, the differences in energy consumption were attributed to the dehumidifying energy costs. Since greenhouse #4 used a heat pump for dehumidification rather than a ventilation and heating system, dehumidifying energy costs could only be compared between greenhouses #1, #2, and #3, but not #4. Nevertheless, the dehumidification efficiency of the heat pump in greenhouse #4 could be compared to that of a conventional heating system in greenhouse #2, as both greenhouses #2 and #4 had a similar water uptake.

Statistical analysis

To study the effect of VPD on hourly water uptake, SAS (1988) was used to perform a repeated measurement analysis. Each trough served as a replicate and each greenhouse served as a treatment. Yield and water uptake, the dependent variables, were correlated to VPD, the independent variable.

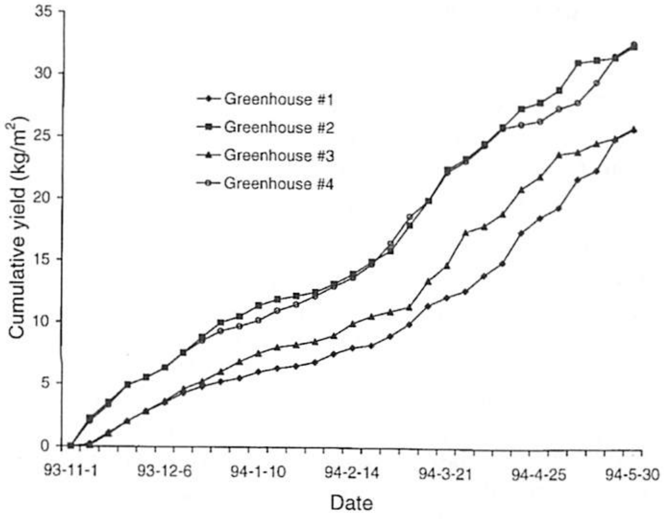

Fig. 4. The cumulative yield measured for the four VPD regimes over the experimental period.

RESULTS and DISCUSSION

Plant water uptake

The mean day, night, and 24 h temperatures and the VPD for the four greenhouses over the entire cropping period are summarized in Table II. For all treatments and greenhouses, the computer system managing the ambient conditions was able to maintain the temperature and VPD set points within a range of +/- 0.5 °C and +/- 0.11 kPa, respectively. Since temperature differences between greenhouses were minimized despite the different ventilation systems, yield, and dehumidification energy cost could be compared for all four VPD treatments (Holder and Cockshull 1990), except for that of greenhouse #4 using a heat pump.

Figure 3 presents the mean hourly rate of plant water uptake, over a typical 24h period and in each greenhouse. Plants in greenhouse #1 with the lowest VPD had the lowest hourly water uptake rate, while plants in greenhouse #2 with a high VPD during both day and night had the highest hourly water uptake rate, on an average. Thus, the VPD level had a significant effect on the hourly water uptake rate. An increase in VPD from 0.4 to 0.8 kPa at mid-day (13:00h) increased the water uptake rate from 35 to 60 mL plant^{-1} h^{-1}. During the day, both greenhouse #3 and #2 had the same VPD, and, compared to greenhouse # 1, their plant water uptake increased by 35% on cloudy days and by 50% on sunny days.

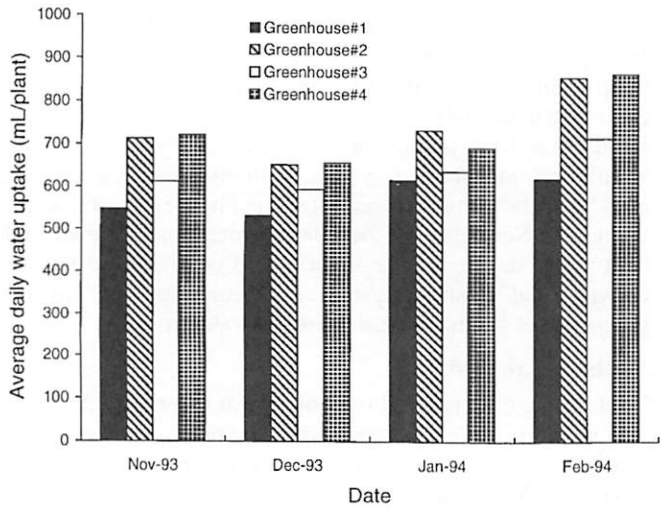

Fig. 5. Average daily plant water uptake for the four VPD regimes during the four experimental periods.

The average daily plant water uptake is presented in Fig. 4 for the four greenhouses and the four months of experimentation. The difference in daily water uptake between greenhouses is similar to that of the hourly water uptake. The mean daily water uptake in greenhouse #4 was generally found to be similar to that of greenhouse #2, except for cloudy days where it was slightly lower. Stanghellini (1987) observed the same trend in water uptake rate when the VPD was varied dynamically.

Daily water uptake also fluctuated on a monthly basis, with the lowest daily water uptake being recorded during December. Daily water uptake increased thereafter, probably because of higher levels of sunlight. The November and January levels of water uptake were similar, with that of February being the highest.

Crop yield

The cumulative marketable fruit yield for the whole experimental period is illustrated in Fig. 5. Greenhouse #1 with a low VPD, produced the lowest yield and had the lowest water uptake rate. Greenhouse #2 with a constant high VPD, had a high yield equivalent to that greenhouse #4, despite the latter's higher level of water uptake. Greenhouse #4 had a dynamically adjusted VPD with a set point maintaining a constant rate of water uptake of 800 mL plant^{-1} d^{-1}. The cumulative effect of VPD on yield tended to become more significant with time. In greenhouse #3, the yield was higher than that in greenhouse #1, but lower than that of greenhouse #2.

These results demonstrate the importance of dehumidification during the day. Dehumidifying increases the VPD and, in turn, increases plant water uptake. Plant yield increases with higher levels of plant water uptake not exceeding 800 mL plant^{-1} d^{-1}.

Energy consumption

The daily energy required to heat and dehumidify all four greenhouses, from November 1993 to February 1994, is summarized in Table III. The price of tomatoes and the energy cost were assumed to be constant throughout this period at Can$2.50 /kg and Can$0.03 /kWh, respectively. The financial gain was calculated by subtracting either the energy cost used for heating and ventilation (greenhouses #1, #2, and #3) or the heating and operating the heat pump (greenhouse #4) from the crop value.

By dehumidifying greenhouse #2 and maintaining its VPD at a high level, its yield and energy consumption were both increased compared to all other greenhouses. By limiting the dehumidification level in greenhouse #1, and maintaining its low VPD, its yield was lower along with its energy consumption, compared to all other greenhouses. Greenhouse #3 had a high VPD during the day and a low VPD at night. Its

Table III. Energy cost versus revenue.

Greenhouse	Water uptake (mL plant^{-1} d^{-1})	Yield (\$ m^{-2} wk^{-1})	Energy (\$ m^{-2} wk^{-1})	Net revenue (\$ m^{-2} wk^{-1})
November 1993				
#1	554	1.15	0.98	0.17
#2	712	2.34	1.75	0.59
#3	612	2.03	1.25	0.77
#4	721	2.09	1.48	0.61
December 1993				
#1	528	0.85	1.69	-0.84
#2	654	1.40	2.52	-1.12
#3	612	1.00	1.74	-0.74
#4	656	1.18	2.15	-0.97
January 1994				
#1	599	0.88	1.17	-0.30
#2	712	1.72	2.35	-0.63
#3	613	0.88	1.58	-0.70
#4	687	1.71	2.02	-0.31
February 1994				
#1	608	1.25	0.82	0.43
#2	837	2.25	1.32	0.93
#3	711	1.63	0.78	0.85
#4	863	2.25	1.28	0.97
Average				
#1	536	1.03	1.17	-0.14
#2	727	1.91	2.00	-0.09
#3	635	1.38	1.35	0.03
#4	729	1.80	1.74	0.06

Note: The energy costs \$0.03/kWh and the crop is valued at \$2.50/kg.
The net advantage equals the yield value less the heating and dehumidifying energy costs.

yield was intermediate and so was its energy consumption. The net profit obtained with greenhouse #1 with a high VPD, was much lower than that of all other greenhouses. Also, greenhouse #2 demonstrated the next lowest net advantage because of its high dehumidification cost. Greenhouse #3 was the most profitable of the three greenhouses (#1, #2, and #3) because of its low energy cost with respect to its revenue.

The net profit of greenhouse #4 could not be compared to that of the other greenhouses, because a different dehumidification system was used. Nevertheless, its net advantage was superior to all other greenhouses. For approximately the same water uptake rate as greenhouse #2, it had a slightly lower yield but a much lower energy cost.

Greenhouse #4 had a lower energy consumption compared to greenhouse #2, as illustrated for February in Table IV. Compared to greenhouse #2 and for a higher level of water uptake, greenhouse #4 required considerably less heat input, because its dehumidification system used a heat pump.

The energy consumed by all four greenhouses and for December and January was higher than the value of the crop harvested. Despite the use of efficient technologies, such as a heat pump and a dynamically adjusted level of water uptake, the costs of producing tomatoes during these months in Québec City exceeded the value of the yield.

By dynamically adjusting the VPD set point in greenhouse #4, the yield was increased, compared to greenhouses #1 and #3. The manipulation of the VPD also had a direct impact on heating and dehumidification energy costs. This justifies the development of a model to predict plant yield and energy consumption based on VPD. Such a model could be used to optimize the management of relative humidity in greenhouses for maximum profit.

CONCLUSION

VPD had a significant effect on the hourly and daily water uptake rates of tomato plants. By using VPD as the only controlled variable, the hourly water uptake rate was increased by 35 to 50%. Increases in water uptake, up to 800 mL plant^{-1} d^{-1}, led to an increased crop yield. However, VPD has an effect not only on plant water uptake and tomatoes yield [***Lycopersicon esculentum Truss***] but also on the energy costs involved. Therefore, any humidity control algorithm must take into account the impact of the VPD on the plant water uptake and yield as well as the energy costs involved in heating and the dehumidification processes.

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REFERENCES

Aikman, D.P. and G. Houter. 1990. Influence of radiation and humidityon transpiration: implications for calcium levels in tomato leaves. *Journal of Horticultural Science* 65: 245-253.

Bakker, J.C. 1990. Effect of day and night humidity on yield and fruit quality of glasshouse tomatoes. *(Lycopersicon esculentum Mill.). Journal of Horticultural Science* 65: 323-331.

Bakker, J.C., G.W.H. Welles and J.A.van Uffelen. 1987. The effects of day and night humidity on yield and quality of glasshouse cucumbers. *Journal of Horticultural Science* 62: 363-370.

De Halleux, D. and L. Gauthier. 1995. Energy consumption due to dehumidification of tomato greenhouse under norther latitude. *HortScience* 30: 35-42.

Grange, R.I. and D.W. Hand. 1987. A review of the effects of atmospheric humidity on the growth of horticultural crops. *Journal of Horticultural Science* 62: 125-134.

Table IV. Energy consumption and transpiration rate for greenhouses #2 and #4 in February 1994.

Date	Energy consumption (10^2 kWh)		Transpiration rate (mL $plant^{-1}$ d^{-1})		To (°C)	Radiation (kW d^{-1} m^{-2})
	#2	#4	#2	#4		
11	1.10	0.62	815	842	-15.6	2.09
12	1.05	0.80	862	873	-10.7	1.88
13	1.13	0.88	803	817	-5.4	1.15
14	1.09	0.87	815	867	-7.3	1.69
15	1.08	0.86	827	849	-11.6	2.01
16	1.05	0.87	856	848	-5.0	2.15
17	1.14	1.01	855	913	-6.7	1.73
18	1.17	0.67	870	883	-5.6	2.48
19	1.20	0.60	846	834	1.5	2.33
20	1.10	0.60	882	953	7.6	1.84
21	1.08	0.63	867	837	3.7	2.06
22	1.05	0.60	874	837	-7.8	2.63
23	1.02	1.00	659	744	-11.5	2.08

Holder, R. and K.E. Cockshull. 1990. Effects of humidity on the growth and yield of glasshouse tomatoes. *Journal of Horticultural Science* 65: 31-39.

Picken, A.J.F. 1984. A review of pollination and fruit set in the tomato (*Lycopersicon esculentum Mill.*). *Journal of Horticultural Science* 59: 1-13.

SAS. 1988. *User's Guide*, Version 6, 1st edition. Cary, NC: SAS Institute Inc.

Stanghellini, C. 1987. Transpiration of greenhouse crops: an aid to climate management. Ph.D. Thesis. Wageningen Agricultural University, Wageningen, The Netherlands.

Stanghellini, C. and W.Th. van Meurs. 1992. Environmental control of crop transpiration. *Journal of Agricultural Engineering Research* 51: 297-311.