Modelling the transpiration of a greenhouse zucchini crop grown under a Mediterranean climate using the Penman-Monteith equation and its simplified version

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Abstract. In Mediterranean climates, high temperatures and vapour pressure deficits are currently observed in greenhouses during summer. These conditions are responsible for a high transpiration rate leading to greater water consumption. Measuring and modelling transpiration can be useful for efficient irrigation management by allowing prediction of short-term water demand. The rate of transpiration of zucchini crops (Cucurbita pepo L.) grown in soilless culture was measured in a greenhouse located at Viterbo, central Italy, during spring-summer 2002. The Penman-Monteith equation was used to predict the potential transpiration of the plants averaged over 30-min intervals using different approaches in the calculation of aerodynamic resistance. The values obtained were compared with transpiration measured by a gravimetric method by weighing plants on an electronic balance. Leaf temperature was lower (up to 5°C) than air temperature on clear summer days owing to high transpiration rates. Stomatal resistance was computed and found to be exponentially related to solar radiation. The best fit in transpiration between the Penman-Monteith calculated and those measured was achieved when the heat transfer in the former was obtained as a process of mixed convection, where the slope of the regression was 1, and there was improvement of the coefficient of determination ($R^2 = 0.96$). A simplified model of daytime transpiration based on easily measured variables (solar radiation and vapour pressure deficit) was developed and produced strong agreement with the gravimetric method ($R^2 = 0.93$).

Additional keywords: Cucurbita pepo L., stomatal resistance, solar radiation, heat transfer coefficient, transpiration.

Introduction

Transpiration plays an important role in the growth and development of crops (Shih 1985; Watts and Goltz 1985). Water management in soilless culture requires more technology and expertise than soil cultivation due to the limited substrate volume, which also restricts availability of nutrients. For these reasons, soilless systems require an accurate and dynamic control of water and fertiliser supply to replenish the continuous depletion through transpiration. Estimation of transpiration can be useful for irrigation control by allowing the prediction of short-term water demands.

Measuring and modelling transpiration over short-time intervals allows a precise evaluation of the crop water requirements. This can therefore aid in the efficient delivery of water and fertiliser supply, especially in areas with a Mediterranean climate, where water is often a scarce natural resource. Precise measurement of transpiration may aid management to avoid stress situations that reduces growth and yield. Alternatively, excess watering wastes water and nutrients and increases environmental pollution.

The most common method of calculating the transpiration of a greenhouse crop is the Penman-Monteith equation (Monteith and Unsworth 1990). This equation is recommended by the United Nations Food and Agriculture Organization (FAO) and by the World Meteorological Organization (WMO). It is preferred to other empirical methods, specifically for short-period estimations under various weather conditions. The Penman-Monteith equation, however, requires the stomatal and the aerodynamic resistances to be known along with the environmental variables within the canopy. This approach has been used in tomato (Stanghellini 1987; Jolliet and Bailey 1992; Boulard and Jemaa 1993), cucumber (Yang et al. 1990), lettuce (Pollet et al. 1999), rose (Baille et al. 1994a), and ornamentals (Bailey et al. 1993; Baille et al. 1994b; Montero et al. 2001). No such data are available for zucchini squash (Cucurbita pepo L.), which is widely grown under unheated greenhouse conditions in the Mediterranean region, especially in Italy (www.istat.it). Most of the greenhouse transpiration research, especially on vegetable crops, has been conducted in temperate and maritime climates of northern Europe.
and North America. Information is limited on the use of the Penman-Monteith model to predict transpiration for greenhouse vegetable crops, especially in the Mediterranean climate that is characterised by high air temperature (>35°C) and vapour pressure deficit (>3 kPa).

The aim of this study was to estimate transpiration rate and stomatal response of zucchini squash and to develop a simplified model of the Penman-Monteith equation to predict transpiration for this crop, using easily measured variables.

Materials and methods

List of abbreviations

cp, Specific heat of air (kJ/kg.K); d, characteristic dimension of the leaf (m); D, vapour pressure deficit (kPa); εn, air vapour pressure (kPa); ε, evaporation flux density (kg/m².s); γ, acceleration due to gravity (m/s²); Gr, Grashof number; h, heat transfer coefficient (W/m².K); Lc, photosynthetically active radiation above the canopy (µmol/m².s); Lp, photosynthetically active radiation below the canopy at the pot level (µmol/m².s); Ls, fraction of photosynthetically active radiation intercepted by the canopy (1 – Lc/Lp); λ, extinction coefficient; λc, thermal conductivity of air (W/m.K); l, length of the leaves (m); L, leaf area index; rC, aerodynamic resistance (s/m); rc, canopy resistance (s/m); rs, stomatal resistance (s/m); Re, Reynolds number; Rs, net radiation (W/m²); R, solar radiation (W/m²); T, air temperature (°C); Ta, base temperature (°C); Tl, leaf temperature (°C); Tm, maximum air temperature (°C); Tm*, minimum air temperature (°C); Tm0, thermal time (°C/day); u, air velocity (m/s); v, width of the leaves (m); λs, gradient of the water saturation vapour pressure curve (kPa/K); α, thermal diffusivity of air (m²/s); β, thermal expansion coefficient of air (K⁻¹); ψ, psychrometer constant (kPa/K); λ, latent heat of evaporation (kJ/kg); ν, kinematic viscosity of air (m²/s); p, density of air (kg/m³);

Theoretical approach

The energy used in transpiration from a crop canopy can be obtained from the Penman-Monteith equation:

\[ \dot{E} = \frac{\lambda C A}{h} + \left[ \frac{(\rho c p) \epsilon \nu}{h} \right] \frac{\nu - \gamma}{\nu + \gamma} \]  

This equation applies to a homogenous crop canopy (‘big leaf approach’), which is not common in practice; therefore, the radiation term must be multiplied by the fraction intercepted by the canopy \([1 - exp(-dL)]\).

Besides the environmental variables (net radiation intercepted by the canopy, air and leaf temperature, and vapour pressure), the \(r_C\) and \(r_s\) have to be accurately assessed. The \(r_C\) value can be directly measured with a porometer, and the measured values can be related to the main environmental variables (solar radiation, vapour pressure deficit, and air temperature). For a hypostomatic crop, the exchange area for latent heat is the leaf area index. Accordingly, a mean canopy resistance, \(r_C\), can be defined as (Bailey et al. 1993; Montes et al. 2001):

\[ r_C = \frac{r_s}{L} \]  

Leaf area index is an easily measurable parameter that greatly influences crop water requirements; however, direct measurements of \(L\) are often laborious and time consuming. Therefore, a submodel based on weather parameters that describes the change in \(L\) as the crop develops is of a practical interest. Some authors (NeSmith 1997) relate leaf number of zucchini squash to temperature using the thermal time approach in the following formula:

\[ TH_T = \sum [TB_{0} - TB] \]  

Two additional constraints are used in the thermal time calculations. If the \(TB\) is less than \(TB_0\) (8°C), then it is set to \(TB_0\); if the \(TB\) exceeds 32°C (ceiling temperature), it is set to \([32 - 2(TB_{0} - 32)]\).

The base temperature and the 32°C ceiling temperature were assumed for these calculations based on the results obtained by NeSmith (1997) on zucchini squash. In our study, Eqn 3 was used to estimate \(L\) during the growing cycle.

The aerodynamic resistance of the canopy to the transfer of vapour can be obtained from the convective heat transfer coefficient, as the eddy diffusion process transports both air and water vapour. The relationship between the canopy resistance and the heat transfer coefficient for individual leaves can be assumed to be (Bailey et al. 1993):

\[ r_C = \frac{\nu \epsilon}{\rho C} \]  

Convective heat transfer is generally analyzed using the Grashof or Reynolds numbers. The numbers of Grashof and Reynolds correspond to the air flow occurring in free and forced convection, respectively. The Grashof number is a function of the temperature difference between the leaf and the air:

\[ Gr = \frac{\rho u^3 l^3}{\gamma} \]  

The Reynolds number can be expressed as a function of air velocity:

\[ Re = \frac{u d}{v} \]  

Leaves are generally thin, so the temperatures of the upper and lower surfaces may be assumed to be equal; therefore, we can use the formula by McAdams (1954) to calculate the average heat transfer coefficient caused by free convection for a given leaf:

\[ h = 0.37 \left( \frac{k}{d} \right) Gr^{0.8} \]  

When moving air comes into contact with a warm body, heat is lost by forced convection. The average value of the heat transfer coefficient for forced convection is given by Gobre and Eék (1961) as:

\[ h = 0.60 \left( \frac{k}{d} \right) Re^{0.8} \]  

In the greenhouse environment, the air is rarely stationary. Stanghellini (1987) found that the convective heat transfer coefficient is due to forced as well as free convection (mixed convection) and proposed the following expression:

\[ h = 0.37 \left( \frac{Gr + 6.92 Re}{d} \right)^{0.8} \]  

In all cases, \(d\), the characteristic dimension of the leaf (m), is defined by:

\[ d = \frac{2}{(1/l) + (1/u)} \]  

Greenhouse facilities and plant material

The experiment was conducted in a polythene 200-m² greenhouse situated at the experimental farm of Tuscia University, central Italy (42°25'N, 12°08'E, alt. 310 m). Inside the greenhouse, ventilation was provided automatically when the air temperature inside the greenhouse exceeded 25°C; the air speed measured ranged between 0.05 and 0.26 m/s, and light was provided only by natural solar radiation.
Modelling transpiration of greenhouse zucchini

The greenhouse floor was covered with a layer of plastic mulch to eliminate the effect of evaporation from the ground surface and to minimise reflection. Uniformly spaced double-channel benches (3.6 m-long by 0.26 m-wide per channel, with a slope of 1.5% and oriented N-S) were used to support potted plants. Zucchini squash (Cucurbita pepo var. Albidotis) was used to form the canopy for this study. Transplanting occurred on 28 March 2002 into 8-L pots filled with a mixture of pumice–peat (2 : 1 v/v). The distance between the centres of double rows (bench) was 1.9 m, and the distance between rows was 0.6 m and between plants in the row was 0.5 m, giving a plant density of 2.1 plants/m². The experiment finished on 17 June 2002. A standard nutrient solution for zucchini having an EC of 1.9 dS/m and pH of 6.0 was supplied via a drip system. The drip system had 1 emitter per plant with a flow rate of 4 L/h. Irrigation scheduling was performed using electronic low tensiometers (LI-Tensiometer). The tensiometers were connected to an electronic programmer that controlled the beginning (−5 kPa) and the end of irrigation (−1 kPa), which correspond to high and low tension set points for the major part of the media (Kiefel et al. 1992). Fruit and flower were harvested 3 times per week starting on 10 May 2002, until the end of the cycle.

Measurements

A separate set of 6 potted plants was placed on an electronic weighing balance (±0.2; Mettler, Switzerland) at the same plant density of the canopy. These plants were in the centre of a bench containing guard plants to form a continuous canopy. The pots were covered with plastic film to minimise evaporation. Measurements were made from 16 April (20 days after transplanting) until the end of the experiment on 17 June. The transpiration rate (W/m²) was recorded every minute and averages were made over 30-min periods. The assumption was made that the weight loss measured by the electronic balance was equal to the crop transpiration. The leachate from the lysimeter was collected and the transpiration data were discarded during leaching periods (av. 30 min after the end of irrigation), which were determined visually.

The following weather data inside the greenhouse were determined: dry and wet bulb air temperature by means of wire resistance thermometers in aspirated boxes; solar radiation (Rₛ) by means of a pyranometer (CM11 Kipp and Zonen, The Netherlands); net radiation (Rₙ) by means of a net radiometer (CNR1, Kipp and Zonen, The Netherlands). Photosynthetically active radiation above the canopy (Lₐ; 400–700 nm) was measured using a LI-COR quantum sensor (LI-908A, Lincoln, Nebraska, USA). Leaf temperature was measured by means of copper-constantan thermocouples (wire diam. 0.1 mm). The thermocouple junctions were glued to the undersides of the leaves. The canopy temperature was used in the analysis, and was taken as the mean value of measurements on 8 healthy and mature leaves distributed randomly throughout the canopy. Air speed was measured using a hot wire anemometer (Airflow Developments Ltd, High Wycombe, UK).

All measurements were collected on a data logger system (CR10X, Campbell Scientific, Inc., UK); the sensors were scanned every minute and the 30-min average values were recorded.

The light intercepted by the canopy was measured using an 80-cm-long quantum flux sensor (Sunfleck Ceptometer, Delta-T Devices Ltd, England) on the 6 plants located in the electronic balance and on the adjacent plants of the same row. Measurements made biweekly during 11–14 h of this time interval, average out the effect of increasing and decreasing solar elevation on light intercepted. The leaf stomatal resistance was measured by a steady-state porometer (LI-COR 1600). Data were collected at 15-day intervals, starting at 20 days after transplanting. On each day where the measurements were performed, data were collected in the morning, around noon, and in the afternoon to cover a wide range of environmental conditions. The maximum length and width of all leaves of 24 plants were measured every 15 days. L was estimated using experimental equations, which were determined from off-trial plants by linear regression of measured leaf areas (Delta T Area Measurements System, England) x calculated areas (max. length x max. width).

Results and discussion

Environmental conditions

The diurnal course of the greenhouse environmental variables (net radiation, leaf and air temperature, vapour pressure deficit, and leaf-air difference temperature) measured on a representative sunny day is shown in Fig. 1. The net radiation inside the greenhouse reached a maximum value of 750 W/m²; the maximum temperatures for the air and leaf were 37.5 and 33.8°C, respectively; and the vapour...
pressure deficit rose from 0.6 kPa early in the morning to 3.6 kPa at 1400 hours. The most important point that should be mentioned is the discrepancy between leaf and air temperature. During the whole experimental period, leaf temperature was found to be consistently lower than air temperature in the daytime; also, leaf and air temperatures were similar before sunrise and after sunset. During the rest of the day, and especially near noon, the difference in leaf–air temperatures reached 5°C. The maximum difference was directly correlated to the maximum solar radiation. In this study, the consistent observation of the leaf temperature being lower than the air temperature was related to the high transpiration rate of the greenhouse zucchini squash. Previous studies have reported that leaf temperature was higher than air temperature during periods of high solar radiation when plants were stressed (Jackson et al. 1981). These findings were mostly observed in studies that were carried out in the open field (Salisbury 1979). The difference between leaf and air temperature was used to develop a crop water stress indicator (Jackson et al. 1981). In greenhouses, leaf temperature depressions ($T_L < T_a$) have frequently been found. Montero et al. (1981) found that leaf temperature was lower than air temperature for tomato crops except when humidity went above 85%. Moreover, research on Ficus benjamina (Bailey et al. 1993), geranium (Montero et al. 2001), and cucumber (Yang et al. 1989, 1990) showed that leaf temperature could be consistently lower than the greenhouse air temperature under well watered plant conditions. By applying the above findings to the case of our experiment, it seems safe to conclude that no stress occurred during the growing cycle of the zucchini. This observation is supported by the fact that leaf temperature was lower than the air temperature.

**Light interception by the canopy**

The leaf area index increased from 0.3 at 24 days after transplantation, to 5.6 at the end of the experiment. $I_{int}$ increased with $L$ (Fig. 2). $I_{int}$ was represented by the law of Lambert-Beer (Monsi and Saeki 1953):

$$I_{int} = 1 - \exp(-kL) \tag{11}$$

The best correlation between $I_{int}$ and $L$ was obtained for $k = 0.76$ ($R^2 = 0.88$), which is in the range indicated by Marcelis et al. (1998). To calculate the energy used in transpiration, the radiation term of the Penman-Monteith equation was multiplied by $I_{int}$. In this way, it was assumed that the fraction of net radiation intercepted by the canopy was similar to $I_{int}$.

**Stomatal resistance**

Stomatal resistance ($r_s$) can be expressed as a function of different environmental factors (Burrows and Milthorpe 1976; Stewart 1989). In our study, a significant relationship between $r_s$ and $L$ was observed (Fig. 3). The best-fit was obtained with the following exponential expression:

$$r_s = 87.30 + 647.24 \times \exp(-0.0022L) \tag{12}$$

Similar results on the effects of solar radiation on stomatal resistance were observed on cucumber (Yang et al. 1990), Ficus benjamina (Bailey et al. 1993), and geranium (Montero et al. 2001). Therefore, we can conclude that under our experimental conditions, in order to calculate transpiration rates the $r_s$ can be accurately estimated as a function of the solar radiation.

**Fig. 2.** Fraction of photosynthetically active radiation intercepted by the canopy ($I_{int} = 1 - I_a/I_a$) vs. leaf area index ($L$) for greenhouse zucchini squash, where $I_a$ is the photosynthetically active radiation at the top of the canopy and $I_{int}$ is the photosynthetically active radiation below the canopy at the pot level. $I_a = 1 - \exp(-0.76d)$, coefficient of determination $R^2 = 0.99$, s.e. of estimate = 0.1.

**Fig. 3.** Instantaneous values of leaf stomatal resistance ($r_s$) measured on zucchini squash with a porometer as a function of photosynthetically active radiation at the top of the canopy ($I_a$) measured during the entire growing cycle. $r_s = 87.30 + 647.24 \times \exp(-0.0022L)$, coefficient of determination $R^2 = 0.95$, s.e. of estimate = 36.2 μmol/m².s.
Crop transpiration

The transpiration rate (mean 30-min values) reached by the canopy was very high (up to 680 W/m² ≡ 0.5 kg/m²).

The daily integration of transpiration was in the range of 0.4–8.2 kg/m² of ground area. This corresponds to 0.19–3.9 l of water per plant per day, which is typical of summer greenhouse zucchini plants (Rouphael et al. 2004).

Calculated v. measured transpiration fluxes together with their regression lines and statistical parameters are shown in Figs 4, 5, 6. Transpiration was calculated from Eqn 1 using the rs values obtained from Eqn 2 and using the rc values derived by Eqn 12. Since rc is difficult to estimate at low radiation values from direct measurements with a porometer (Lu et al. 2013), only data for solar radiation above 25 W/m² were considered. The Penman-Monteith equation well reproduced transpiration values recorded in the experiment (R² > 0.95). Model estimation improved with forced or with mixed convection in comparison with free convection, consistent with the improvement in the slope of the regression (Figs 4, 5, 6).

The slope of the regression line for free convection was lower than 1, which indicates that the model systematically underestimates the transpiration fluxes. It is clear that under our conditions, rc appeared to be related more closely to the heat transfer coefficient for forced and especially for mixed convection. A common tool for evaluating whether heat transfer from a surface is caused by free or forced convection.

Fig. 4. Calculated daytime transpiration rates (30-min average) by the Penman-Monteith equation assuming free convection (λEcal) v. measured transpiration rates (λEmes, electronic weighing balance) of greenhouse zucchini squash. λEcal = 0.93 λEmes + 0.50, coefficient of determination R² = 0.93, s.e. of estimate = 26.9 W/m², N = 728 values.

Fig. 5. Calculated daytime transpiration rates (30-min average) by the Penman-Monteith equation assuming forced convection (λEcal) v. measured transpiration rates (λEmes, electronic weighing balance) of greenhouse zucchini squash. λEcal = 0.99 λEmes − 4.21, coefficient of determination R² = 0.95, s.e. of estimate = 28.2 W/m², N = 728 values.

Fig. 6. Calculated daytime transpiration rates (30-min average) by the Penman-Monteith equation assuming mixed convection (λEcal) v. measured transpiration rates (λEmes, electronic weighing balance) of greenhouse zucchini squash. λEcal = 1.00 λEmes − 3.35, coefficient of determination R² = 0.96, s.e. of estimate = 26.5 W/m², N = 728 values.
is to compare the relative magnitude of $Gr$ and $Re$ numbers (Stanghellini 1987). Heat transfer is caused by free convection when $Gr$ is much larger than $Re^2$, whereas forced convection occurs when $Gr$ is much smaller than $Re^2$. Based on this approach, we found that in about 70% of cases the heat transfer occurred by free convection and in 30% by forced convection (when the ventilator was turned on). The above findings confirm that, in our conditions, the heat transfer was caused by both free and forced convection (mixed convection).

Simplified model

Simplified models for predicting water consumption by crops can be used as a rational basis for scheduling plant irrigation. For this reason, correlations linking $\lambda E$ to $Rs$, $D$, and $L$ have been proposed (Baille et al. 1994c). The following relationship derived from the simplified form of the Penman-Monteith equation was chosen:

$$\lambda E = A_{int}Rs + BLD$$

where $A$ and $B$ correspond to the coefficients of the radiative and advective components, respectively ($A$, dimensionless; $B$, kg/m².h.kPa). Both coefficients can be identified by using regression analysis between measured transpiration rate and crop ($L$) and environmental parameters ($Rs$ and $D$).

A non-linear relationship was apparent between thermal time and $L$ (Fig. 7), giving the following equation ($R^2 = 0.98$):

$$L = 11.2 \exp(-7.65 \exp(-0.0029THT))$$

A multiple linear regression was established between the measured transpiration rates and the radiative and advective terms of Eqn 13, taking into consideration only daytime transpiration. The regression yielded:

$$\lambda E = 0.63I_{int}Rs + 6.49LD$$

The coefficient of determination was $R^2 = 0.93$ and the standard errors in estimating the coefficients of the radiative and advective terms were 0.008 and 0.387, respectively; and the standard error in estimating daytime $\lambda E$ was 33.2 W/m².

The simplified model Eqn 15 proposed for predicting short-term rates of transpiration for zucchini squash under our experimental conditions produced agreement with measured data (Fig. 8). From a practical standpoint, such a model could be easily implemented in algorithms for zucchini daytime irrigation control, as $Rs$ and $D$ are 2 variables currently monitored in the greenhouse; the only problem is the determination of $L$. Correlations giving $L$ vs. thermal time would be the most convenient way to estimate $L$ as reported in Eqn 14.

Conclusions

This study has shown that the Penman-Monteith equation accurately predicted the transpiration rate of zucchini grown under high temperatures and vapour pressure deficits. The stomatal resistance was closely correlated with solar radiation and thus can be predicted from radiation measurements. Leaf temperatures of zucchini plants were found to be consistently lower than air temperature during daytime. The best-fit comparison between calculated and measured transpiration...
was obtained when the heat transfer from the leaves to the environment was considered to be forced or mixed convection. Finally, a simplified model of transpiration rate that included easily measured variables was considered to be sufficiently robust to be used for greenhouse irrigation scheduling.

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