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A Simple Model for Predicting Transpiration of Greenhouse Cucumber

Ein einfaches Modell für die Vorhersage der Transpiration von Gewächshausgurken

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Summary

A simple model is presented that predicts transpiration of a greenhouse cucumber crop. Leaf area development, which is important for transpiration prediction at least until complete soil cover, is calculated from a simple dry matter production derived model. This model calculates total dry matter production from intercepted radiation and light use efficiency, leaf area growth is determined from the fraction of dry matter allocated to the leaves and the specific leaf area. The calculation of crop transpiration itself is based on the Penman-Monteith approach. For parametrisation and validation of the model data of two previously published experiments with greenhouse cucumber at different locations (Wageningen and Hannover) were used.

The determination of the aerodynamic and the canopy resistance of the Penman-Monteith equation was done by adjusting these parameters with respect to experimental data. Applied to independent data the model was able to predict leaf area development until complete soil cover ($r^2 > 0.95$) and daily water consumption of cucumber ($r^2 > 0.75$). Compared with results of a multiple linear regression analysis of daily water use dependent on radiation and vapour pressure deficits, the presented model showed its superior predictive value especially during the youth period of the crop when soil cover was incomplete.

Zusammenfassung

Ein einfaches, teilweise empirisches Simulationsmodell wird vorgestellt, das die Transpiration von Gewächshausgurkenbeständen berechnet. Die Blattflächenentwicklung des Bestandes wird im Modell ausgehend von der durch den Bestand aufgenommenen photosynthetisch aktiven Strahlungsenergie, dem Lichtnutzungskoeffizienten und der sich hieraus ergebenden Trockenmassezuwachsrate sowie dem Anteil der auf das Blatt entfallenden Trockenmassezuwachsrate und der spezifischen Blattfläche berechnet. Die Berechnung der Bestandesverdunstung selbst erfolgt mit Hilfe des Penman-Monteith Ansatzes. Für die Parametrisierung und Validierung des Modelles wurden Daten aus zwei publizierten Versuchen mit Gewächshausgurken an unterschiedlichen Orten (Wageningen und Hannover) benutzt.

Die Bestimmung des in der Penman-Monteith Gleichung benötigten aerodynamischen und Bestandeswiderstandes erfolgte durch Anpassung des Modelles an einen Teil der zur Verfügung stehenden experimentellen Daten. Bei der Anwendung des Modelles an unabhängige Daten zeigte sich, dass das Modell in der Lage war, die Blattflächenentwicklung ($r^2 > 0.95$) und den täglichen Wasserverbrauch der Gewächshausgurkenbestände ($r^2 > 0.75$) zu prognostizieren. Ein Vergleich mit Ergebnissen einer multiplen linearen Regression der täglichen Transpiration in Abhängigkeit von der Strahlungssumme und dem mittleren Sättigungsdefizit zeigte insbesondere während der Jugendphase der Bestände eine höhere Vorhersagegenauigkeit des vorgestellten Modelles.

Introduction

The dry matter production of greenhouse cucumber (*Cucumis sativus* L.) is critically influenced by an adequate water supply to the plants. In order to avoid deficiencies of water supply and because the water requirement of a greenhouse crop is not easily determined, growers often irrigate more than is needed for optimal growth. In soil-grown cucumber and other open growth media systems, where irrigation is often technically coupled with fertilisation, this results in nutrient losses due to leaching, especially for nitrate (SONNEVELD 1981).

A more precise irrigation scheduling may be achieved by the use of water balance models, which calculate the water requirement of the crop and the actual water supply in the soil or growth medium as function of the environmental conditions. Because the transpiration rate increases with increasing leaf area at least until complete soil cover of the crop (BAILLE *et al*. 1994), models used for irrigation control also should calculate growth processes in order to predict the leaf development of the crop.

Transpiration models for greenhouse crops of different complexity have been developed ranging from quite detailed models with high temporal and spatial resolution (STANGHELLINI 1987) to more comprehensive (BAILLE *et al*. 1994, HAMER 1997) and empirical approaches (HEISSNER 1997). Existing water balance models for greenhouse crops, however, are seldom coupled with crop growth models and mostly need crop parameters like the leaf area index as input values. Unfortunately, these data are in practice seldom available.

In order to overcome these shortcomings, the aim of this study is to examine if a simple, easily parameterised simulation model for growth and water balance of a soil grown greenhouse cucumber crop is able to predict leaf development and water use of greenhouse cucumber.

Material and Methods

Model

As stated above the model consists of two parts, a simple dry matter production model and an evapotranspiration model.

Dry Matter Production

Existing dry matter production models for greenhouse crops and crops in unprotected cultivaton differ widely in complexity and scope (a recent review can be found in MARCELIS *et al*. (1998)). For the purpose of this study we used the probably most simplifying light use efficiency approach (MONTEITH 1977) for calculating dry matter production.

The growth rate of dry matter of a crop, dW/dt, ($g \cdot m^{-2} \cdot d^{-1}$) may be calculated as a linear function of absorbed photosynthetically active radiation (PAR) Q ($MJ \cdot m^{-2} \cdot d^{-1}$) using the empirical light use efficiency coefficient ε ($g \cdot MJ^{-1}$):

$$\frac{dW}{dt} = Q \cdot \varepsilon \quad (1)$$

Values of ε may be obtained by linear regression analysis of daily dry matter growth rate and daily sums of intercepted PAR.

The amount of absorbed photosynthetically active radiation is calculated from the intensity of PAR above the plant canopy, S ($MJ\ m^{-2} \cdot d^{-1}$), and the leaf area index LAI ($m^2\ m^{-2}$) (MONSI and SAEKI 1953)

$$Q = S \cdot (1 - e^{-k \cdot LAI}) \quad (2)$$

The light extinction coefficient k in the above equation depends on several factors like the reflection and transmission coefficients of the leaves, the leaf angle distribution and the light intensity distribution over the sky (GOUDRIAAN 1977). Typical values of k are in the range of 0.5 to 0.8 (MARCELIS *et al*. 1998). Since no measurements of k were available from the experiments used in this study and because of the more planophile leaf orientation of cucumber plants a value for k of 0.8 was assumed.

If no measurements of radiation intensity inside the greenhouse are available S can be calculated from the intensity of the incident global radiation, GR, outside the greenhouse and the light transmission of the greenhouse, t, as well as the fraction of photosynthetic radiation in the total spectrum, f_{PAR}.

$$S = GR \cdot t \cdot f_{PAR} \quad (3)$$

The value of f_{PAR} is usually taken to be 0.5 (SZEICZ 1974). Reflection of visible radiation from the crop, which is about 6% (MONTEITH and UNSWORTH 1990), was neglected.

Dry Matter Partitioning

The total growth rate of a plant dW_t/dt can formally be divided into the growth rates of the vegetative organs, stem W_S/dt, leaf W_L/dt and root W_R/dt, and the growth rate of the generative organs W_F/dt. The dry matter growth rate of any organ i, dWi/dt_i, may then be expressed as a fraction f_i of the total dry matter growth rate dW_t/dt:

$$\frac{dW_i}{dt} = \frac{dW_t}{dt} \cdot f; \quad (4)$$

The fraction of dry matter allocated to a specific organ itself depends on the growth stage of the plant which may be described as a function of the temperature sum (TS) the plant has experienced. A sudden shift in dry matter allocation usually occurs after the start of fruit growth when the fruits become the major sinks in cucumber plants.

The leaf area index, LAI, is calculated from the leaf dry matter W_L ($g \cdot m^{-2}$) using an average specific leaf area (SLA) ($m^2 \cdot g^{-1}$). Since no detailed measurements of SLA during the whole growth period of cucumber were available, we assumed that SLA is constant over time.

Evapotranspiration

We used the Penman-Monteith equation (MONTEITH 1973) which is one of the most fundamental methods to calculate the evaporation rate of a closed plant canopy. This approach is mostly used for closed homogenous plant communities under conditions of unprotected cultivation, but it can also be adopted to greenhouse conditions (STANGHELLINI 1987). The value of the net radiation needed in the Penman-Monteith equation was computed from the global radiation inside the greenhouse and a reflection coefficient of the canopy for total radiation of 0.12 (MONTEITH and UNSWORTH 1990). The radiation energy emitted from the heating system was neglected in the presented analysis.

Crucial but difficulty to determine parameters in the Penman-Monteith equation are the aerodynamic r_a ($s \cdot m^{-1}$) and the canopy r_c ($s \cdot m^{-1}$) resistances. We tried two different approaches to evaluate the value of r_c.

1. Calculation from the LAI of the crop and the stomata resistances, r_s, of the plant leaves. The value of r_s is not constant but is related to environmental variables like light intensity and saturation deficit of the air but also to plant internal variables like leaf water potential and turgor and is also under hormonal control (ABA) (TARDIEU 1993). We tried to calculate r_s from an empirical regression equation relating r_s with light intensity and vapour saturation deficit derived from measurements of FRICKE (1992) (data not shown), however, this approach failed.

2. Parameter estimation from adjusting the calculated daily water consumption to a part of the available experimental data on water consumption of the cucumber crop.

In order to analyse the sensitivity of the Penman-Monteith equation on changes of r_a and r_c more thoroughly, we used the approach of JARVIS and MCNAUGHTON (1986), who divided the Penman-Monteith equation into two components, the equilibrium transpiration E_{eq} ($kg \cdot m^{-2} \cdot s^{-1}$) and the imposed transpiration E_{imp} ($kg \cdot m^{-2} \cdot s^{-1}$).

The equilibrium transpiration depends solely on the net radiation input R_n and is independent from the aerodynamic and canopy resistance:

Table 1. Climatic treatments used in the experiments of (FRICKE and KRUG, 1997b) and average vapour pressure deficit (hPa) in 1987 and 1988.
In den Experimenten von FRICKE und KRUG (1997b) durchgeführte Klimabehandlungen sowie mittlere Sättigungsdefizite (hPa) während der Kulturzeiten.

Treatment	opening of ventilation	average vapour pressure deficit	
		1987	1988
Normal dehumidification	at 6.0 hPa vapour pressure deficit	5.9	7.2
Intensive dehumidification	at 3.0 hPa vapour pressure deficit	7.0	7.1
Control (24 °)	at 24 °C greenhouse air temperature	5.9	6.7
Control (28 °C)	at 28 °C greenhouse air temperature	5.7	6.1

$$E_{eq} = s/\gamma\left(\frac{R_n}{\lambda(s/\gamma+1)}\right) \quad (5)$$

"Here, s is the slope of the vapour saturation curve (hPa · K^{-1}), γ the psychrometer constand (hPa · K^{-1}) and λ the latent heat of vaporisation of water (J · kg^{-1})."

The imposed transpiration part, however, describes the part of the transpiration which originates from the vapour concentration gradient $e_s - e_a$ above the plant canopy:

$$E_{imp} = \frac{\rho_a \cdot c_p \frac{(e_s - e_a)}{r_a}}{\lambda \cdot \gamma} \quad (6)$$

"Where c_p is the volumetric heat capacity of dry air (J · kg^{-1}) and ρ_a the density of dry air (kg · m^{-3})".

Total transpiration is the sum of imposed and equilibrium transpiration:

$$E = \Omega \cdot E_{eq} + (1-\Omega) \cdot E_{imp} \quad (7)$$

Where the parameter Ω in equ. 7 describes the relative contribution of the equilibrium part of plant evaporation (JARVIS and MCNAUGHTON 1986). It's value determined by the ratio of canopy and aerodynamic resistance (JONES 1992):

$$\Omega = \frac{s/\gamma + 1}{s/\gamma + 1 + \frac{r_c}{r_a}} \quad (8)$$

In unprotected cultivation, the boundary layer above the leaf surface is small and the parameter r_a is mainly determined by the windspeed. In protected greenhouse conditions, however, r_a is substantially higher, the boundary layer dominates the overall diffusion resistance and the dimension of the leaves becomes the major factor determining r_a (BAILEY et al. 1993). Since for the experiments used no measurements of the windspeed in the glasshouses were available, we treated also r_a as an empirical parameter, estimated by adjusting our model to a subset of the available data.

Evaporation as calculated from equation (7) is the sum of plant transpiration T_p, and soil evaporation E_s. Plant transpiration was calculated from the amount of net radiation (R_n), the plants intercepted (RITCHIE 1972). The extinction coefficient for total radiation k' of the canopy was calculated from the extinction coefficient for PAR, k, according to MONTEITH and UNSWORTH (1990) $k' = k/1.34$.

Experimental data

The growth-model was parameterised with data from an experiment of MARCELIS (1992) with greenhouse cultivated cucumber. For a detailed description of the experiment see MARCELIS (1992). From this experiment data of global radiation (MJ · m^{-2} · d^{-1}), plant-growth-rate (g · m^{-2} · d^{-1}), fruit-growth-rate (g · m^{-2} · d^{-1}), vegetative-growth-rate (g · m^{-2} · d^{-1}) between the 7th of April and the 27th of June 1990 were available.

MARCELIS (1994) reported only total dry-matter production rates and fractions of vegetative and generative plant parts. In order to get some information about the relative dry matter fractions of leaves, stems and roots in the vegetative dry matter, we separated young, six-leaf-stage cucumber plants with an average dry matter of 1.42 (g · plant^{-1}) into their different organs and measured leaf area and dry matter of the different organs. From these measurements we estimated the fractions of leaves, stem and roots to be 0.72, 0.18 and 0.1 of the vegetative dry matter, respectively. We took this dry weight ratio of the fractions as an estimate for the portions of dry matter allocated to the respective vegetative organs and assumed it to be constant. From leaf area measurements and the leaf dry weight a specific leaf area (SLA) of 380 cm^2 · g^{-1} was calculated.

Data of another two year greenhouse experiment (FRICKE and KRUG 1997a,b) were used for the parametrisation and validation of the transpiration part of the model. In this experiment the quantitative influence of water supply on the productivity of cucumber in protected cultivation was evaluated. We included in our analysis only 4 of the 6 climatic treatments, neglecting the treatments with frequently humidification spraying (Table 1).

The experiment was conducted in greenhouses with 120 m^2 area and a height of 3.0 m. The plants were sown on the 9th of April for 1987 and on the 11th of April for 1988 and planted four weeks later in the 3 to 5 leaf stage. Every greenhouse had three rows with spacings of 1.8 m. There have been 56 plants with 30 cm spacing in one row, resulting in an average plant density of 1.67 plants per m^2. For a more detailed description of the experiment see FRICKE and KRUG (1997a); FRICKE and KRUG (1997b). Data of temperature, leaf evaporation, radiation, leaf area and the vapour pressure deficit were collected during this experiment.

Leaf area, LA (cm^2), of cucumber plants was calculated from weekly measurements of leaf width, LW (cm), and leaf length, LL (cm), using an empirical regression between the product of leaf width and length and the leaf area (LA = 0.875*LL*LW). The latter was measured with a leaf area meter (LI 3100, LI-COR Inc.). The

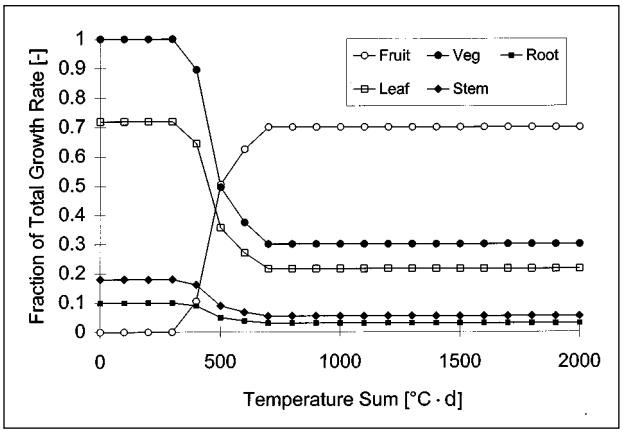


Fig. 1. Growth rates of cucumber-organs (fruit, vegetative, stem, root, leaf) relative to the whole dry-matter growth rate as a function of the temperature-sum since transplanting.
Wachstumsraten einzelner Gurkenorgane (Frucht, vegetative Organe, Stengel, Wurzeln, Blätter) relativ zur Gesamtwachstumsrate als Funktion der Temperatursumme seit der Pflanzung.

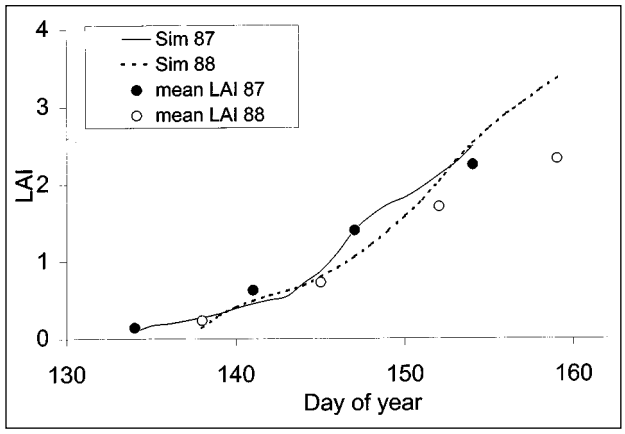


Fig. 2. Comparison of measured (LAI 87, LAI 88) and simulated leaf area index (Sim 87, Sim 88) for cucumber-plants during the Years 1987 and 1988 according FRICKE (1992).
Vergleich von gemessenem und berechnetem Blattflächenindex (LAI) für Gewächshausgurkenbestände in den Jahren 1987 und 1988 (Daten aus FRICKE, 1992).

water use of every greenhouse was measured daily by a flowmeter (Neuhof, QN6 class B). However, the measurements of water loss from the system were carried out between 7.00 and 8.00 am every morning, therefore the measured water consumption is not always exactly representative for the water use of the last 24 hours.

The initial values for the dry matter of the different organs were estimated from leaf area index data in the case of the experiments of FRICKE and KRUG (1997b). In the experiment of MARCELIS (1994), however, the leaf area index was estimated from the reported total dry matter growth rate and the photosynthetically radiation intensity above the cucumber crop. From this data the inital LAI was estimated to be about 0.48. The initial values of the dry matter of the organs were adjusted according to this value.

Model implementation and parameter estimation

The model equations were programmed in Pascal. Integration was performed using time steps of one hour for the calculation of evaporation and of one day for the calculation of the plant growth processes using the Euler algorithm.

The parameters r_a and r_c were estimated using a least squares fit of simulated to measured water consumption rate of the plants using the data from the experiment of 1987. This was done by reformulating the model and passing it as a parameter to a procedure which is based on the Marquardt method (MARQUARDT 1963) and uses the algorithm from PRESS *et al.* (1986). For some test functions results from this fitting routine were compared with the outcome of the procedure NLIN of the statistical software package SAS (SAS Institute 1988).

Results

According to the results of MARCELIS (1992) and our own measurements of dry matter fractions of young, six leaf stage cucumber plants we derived dry matter partitioning table (Fig. 1), which was used in the model to calculate the fractions of the growth rates of the single organs to the total growth rate as a function of the temperature sum assuming a base temperature of 0 °C.

Using the data from the experiment of MARCELIS (1992), neglecting the youth period with incomplete interception of radiation and assuming complete radiation interception for the rest of the growth period we computed a linear regression between growth rate (dWt/dt) and S. This resulted in an estimate for LUE of 2.38 (±0.05) ($g \cdot MJ^{-1}$).

The model for dry matter production was validated by comparing simulated and measured data of LAI from FRICKE (1992) in two experimental years 1987 and 1988. The model was able to predict the leaf area development in 1987 for all 4 sampling dates, in 1988 the last sampling date the LAI was overestimated by the model considerably (Fig. 2). The linear regression between measured and simulated LAI resulted therefore in 1987 in a good agreement with an r^2 of 0.98 and a slope of 1.01. In 1988, however, the coefficient of determination again had a high value of 0.96, but the slope was with a value of 0.74 substantially lower than 1 due to the last measured LAI value.

Adjusting the parameters r_a and r_c of the transpiration model resulted generally in high standard errors for r_a (Table 2). The tendentious highest errors causes from the dehumidification treatments which had a higher frequency of ventilation and therefore probably higher windspeed. There was also a considerable difference between the estimates of r_a for the both different years 1987 and 1988. The estimation of r_c was more precise, the standard errors being usually less than 10% of the mean value. Differences of the parameter estimates for r_c are not obvious. Both parameters seem to be correlated, but not systematically. The resulting values of the coupling factor Ω are in the range of 0.34 to 0.81, the higher values estimated for the control treatments, with less frequent ventilation, as one would expect. The coefficient of determination of the calculated transpiration rates ranges from 0.65 to 0.84.

Table 2. Estimated aerodynamic resistance, r_a, ($s \cdot m^{-1}$) and canopy resistance, r_c, ($s \cdot m^{-1}$), coupling factor, **Ω**, correlation coefficient between r_a and r_c, C, and coefficient of determination, r^2, for simulated transpiration rate of cucumber crops grown in 1987 and 1988 under 4 different climatic treatments.
*Geschätzte aerodynamische, r_a, ($s \cdot m^{-1}$) und Bestandeswiderstände r_c, ($s \cdot m^{-1}$), Kopplungsfaktor **Ω**, Korrelationskoeffizient C zwischen r_a und r_c sowie Bestimmheitsmaß, r^2, der simulierten Transpirationsraten von Gewächshausgurken in den Versuchsjahren 1987 und 1988. Die Berechnungen wurden getrennt für 4 unterschiedliche Klimabehandlungen sowie im Mittel der Entfeuchtungs-, Befeuchtungsvarianten und aller Varianten durchgeführt.*

Year	Treatment	r_a	r_c	Ω	C	r^2
1987	Normal dehumidification	69 (±37)	115 (±10)	0.66	–0.32	0.82
1987	Intensive dehumidification	61 (±43)	177 (±19)	0.53	0.74	0.65
1987	Control (24°)	141 (±59)	103 (±14)	0.81	–0.05	0.84
1987	Control (28°C)	151 (±1034)	275 (±87)	0.64	0.97	0.80
1988	Normal dehumidification	26 (±11)	161 (±5)	0.34	0.07	0.73
1988	Intensive dehumidification	29 (±9)	155 (±4)	0.37	–0.10	0.74
1988	Control (24°)	69 (±27)	128 (±9)	0.63	–0.55	0.75
1988	Control (28°C)	79 (±37)	141 (±9)	0.64	0.24	0.75
1987	All	106	168	0.66		
1988	All	51	146	0.50		
1987	Dehumidification treatments	65	146	0.60		
1987	Control	146	189	0.73		
Both	Dehumidification treatments	46	152	0.48		
Both	Control	110	162	0.68		

We then compared the predictive value of the model with linear regressions of water consumption on both main driving forces of transpiration: radiation intensity and vapour pressure deficit. We performed our analysis either for the whole growth period or neglected the first 20 days in the greenhouse during the crop cover was incomplete.

The regression analysis clearly shows the dominating influence of radiation on the transpiration process (Table 3). For the growing period with complete soil cover 64% and 68% of the variation in daily water consumption could be explained with the daily radiation sum for the years 1987 and 1988, respectively. This is higher than the coefficients of determination values gained from a linear regression on the vapour pressure deficit of 0.52 in 1987 and 0.59 in 1988. The multiple linear regression including both determinants of transpiration gave the highest value of r-square but only slightly higher than with using only radiation data as a regression variable. Including the youth period in the regression analysis drops the coefficient of determination drastically down to values lower than 0.5.

We proved the predictive value of both model approaches, our Penman-Monteith based approach and the multiple regression approach, using the parameters values gained from analysis of 1987 data for the prediction of water use in 1988. We thereby used parameter values for r_a and r_c averaged over the dehumidification and the control treatments individually.

The daily water use calculated with the Penman-Monteith based approach matches usually quite close the measured values for the different dehumidification treatments (Fig. 3) and the calculated values follow after complete soil cover quite close the time course of global radiation. Compared with the outcome of the Penman-Monteith based calculation the predictive value of the linear regression model is clearly inferior if compared for the whole growth period (Table 4). However, some of this inferiority is lost, when the youth period is neglected from the analysis. In this case the multiple linear regression was even when parameterised from an independent data set able to explain about 70% of the observed variation in daily plant water consumption, however, the slope of the linear regression between calculated and measured data was considerably lower.

Discussion

The aim of this study was to examine the predictive value of a simple and easily parameterised model of transpiration of greenhouse cucumber crops. The model parts for dry matter production and partitioning are only included to estimate leaf area expansion as a prerequisite to predict soil cover and are not intended to predict cucumber fruit production.

The assumption underlying the dry matter production model that the growth rate of the cucumber crop is a linear function of the intercepted amount of radiation seems to be valid. The light use efficiency estimated from the experiment of MARCELIS (1992) could successfully used for calculation of dry matter production of the experiments of FRICKE (1992). It is known that LUE is a quite conservative parameter at least for the C3 group of plants (MONTEITH 1977). But also serious variations of LUE even for a particular species are

Table 3. Results of linear and multiple linear regressions between daily water use, wu ($l \cdot m^{-2} \cdot d^{-1}$), of cucumber crops grown in 1987 and 1988 under different climates and the average daily water pressure deficit de (hPa), and daily global radiation GS ($MJ \cdot m^{-2} \cdot d^{-1}$) incident on the outside of the glasshouse including either all available data or omitting the first 20 days from transplanting into the greenhouse ($wu = a \cdot de + b \cdot GS + c$).
Ergebnisse einer multiplen linearen Regression zwischen täglichem Wasserverbrauch (wu) ($l \cdot m^{-2} \cdot d^{-1}$) von Gewächshausgurkenbeständen, die in den Jahren 1987 und 1988 unter verschiedenen Klimabehandlungen wuchsen und dem durchschnittlichen täglichen Sättigungsdefizit (de) (hPa) sowie der täglichen Globalstrahlungssumme GS ($MJ \cdot m^{-2} \cdot d^{-1}$) ausserhalb des Gewächshauses unter Berücksichtigung bzw. Nichtberücksichtigung der Wasserverbrauchsdaten der ersten 20 Tage nach Pflanzung in das Gewächshaus ($wu = a \cdot de + b \cdot GS + c$).

year	period (day)	a	b	c	r^2
1987	134–239	–0.0908 (±0.0184)	0.1539 (±0.0094)	0.6443 (±0.1070)	0.46
			0.1210 (±0.0068)	0.5876 (±0.1092)	0.43
		0.1239 (±0.0166)		1.6460 (±0.1121)	0.12
	154–239	0.1053 (±0.0202)	0.1128 (±0.0090)	0.3714 (±0.0906)	0.67
			0.1488 (±0.0060)	0.4043 (±0.0937)	0.64
		0.2993 (±0.0157)		0.9818 (±0.0920)	0.52
1988	137–249	–0.1288 (±0.2055)	0.1507 (±0.0089)	1.0689 (±0.1006)	0.47
		–	0.1084 (±0.0061)	0.8589 (±0.0990)	0.42
		0.1327 (±0.1728)	–	1.625 (±0.1225)	0.12
	157-249	0.1244 (±0.2106)	0.0920 (±0.0078)	0.5640 (±0.0807)	0.71
		–	0.1292 (±0.0048)	0.7764 (±0.0761)	0.68
		3.2683 (±0.1456)	–	0.6835 (±0.0946)	0.59

described in the literature depending on the water vapour saturation of the ambient air and on the light intensity level (MANRIQUE *et al*. 1991, STOCKLE and KINIRY 1990). However, these parameters and also temperature usually does not change substantially in greenhouse cultivation, so that quite stable value of LUE for a particular crop can be expected. However, the model does not consider the effects of artificially elevated CO_2 levels, which will seriously increase light use efficiency values. This may be seen as a serious shortcoming of the model presented, however, corrections of LUE based on empirical results or derived from analysis of more mechanistic models (GOUDRIAAN and VAN LAAR 1994) may be used instead of a constant LUE.

The very crude procedure for estimating the partitioning coefficients in combination with a constant specific leaf area was able to predict the early leaf area development until almost complete soil cover in the experiments of FRICKE (1992). This is the essential outcome of a dry matter production model with respect to crop transpiration. However, a model in the presented form will fail to predict fruit production patterns, as it does not take account of the cyclic pattern of dry matter distribution to the fruits reported by LIEBIG (1978) and MARCELIS (1992). Furthermore it predicts unrealistically high values of LAI for the end of the growing season (data not shown) as it does not consider leaf senescence and a decrease of SLA during cucumber development.

Due to the high leaf diameter and due to the low windspeed which is common under greenhouse conditions values of r_a well above 200 $s \cdot m^{-1}$ should be found for greenhouse grown cucumber crops (STANGHELLINI 1987). Our analysis gave lower values, even for the control treatments, which were not frequently ventilated as the dehumidification treatments, however, with quite high standard errors of the parameter estimates. As the information about the relative magnitudes of the resistances r_a and r_c originates from the different response of measured cucumber transpiration on changes in vapour saturation deficit and intercepted net radiation, one may argue that errors may have occurred in the measurement of these data. However, changing both input data values by ±10% did not change the parameter values estimated for r_a and r_c and especially their ratio substantially (data not shown). The value of r_a was consistently lower than the value of r_c. The reason for this imprecise estimation of r_a is probably the insensitivity of the Penman equation to a change of r_a if evaluated with r_c values around 150 $s \cdot m^{-1}$ (Fig. 4).

It can also be deduced from Fig. 4 that for practical purposes the error in transpiration estimation resulting from the parameter uncertainty of r_a and r_c is not too critical if the value of r_a is around 100 $s \cdot m^{-2}$ or higher. This should be the case for practically orientated climate control regimes in greenhouses. Under these conditions the value of the coupling factor Ω should be well above 0.6 and net radiation input should mainly determining the transpiration rate. This statement is supported by the results of our calculations, where we used the parameter values obtained from the transpiration data of 1987 for predicting the transpiration in 1988. Despite the substantially different parameter values, the prediction of transpiration was still acceptable (Table 4 and Figure 3) and superior to the multiple linear regression analysis (Table 4). The Penman-Monteith equation in combination with simple, easily parameterised dry matter production based models of leaf area development seems therefore even under greenhouse conditions to be a quite robust and applicable approach. It should therefore gain more consideration even for practically oriented greenhouse irrigation scheduling.

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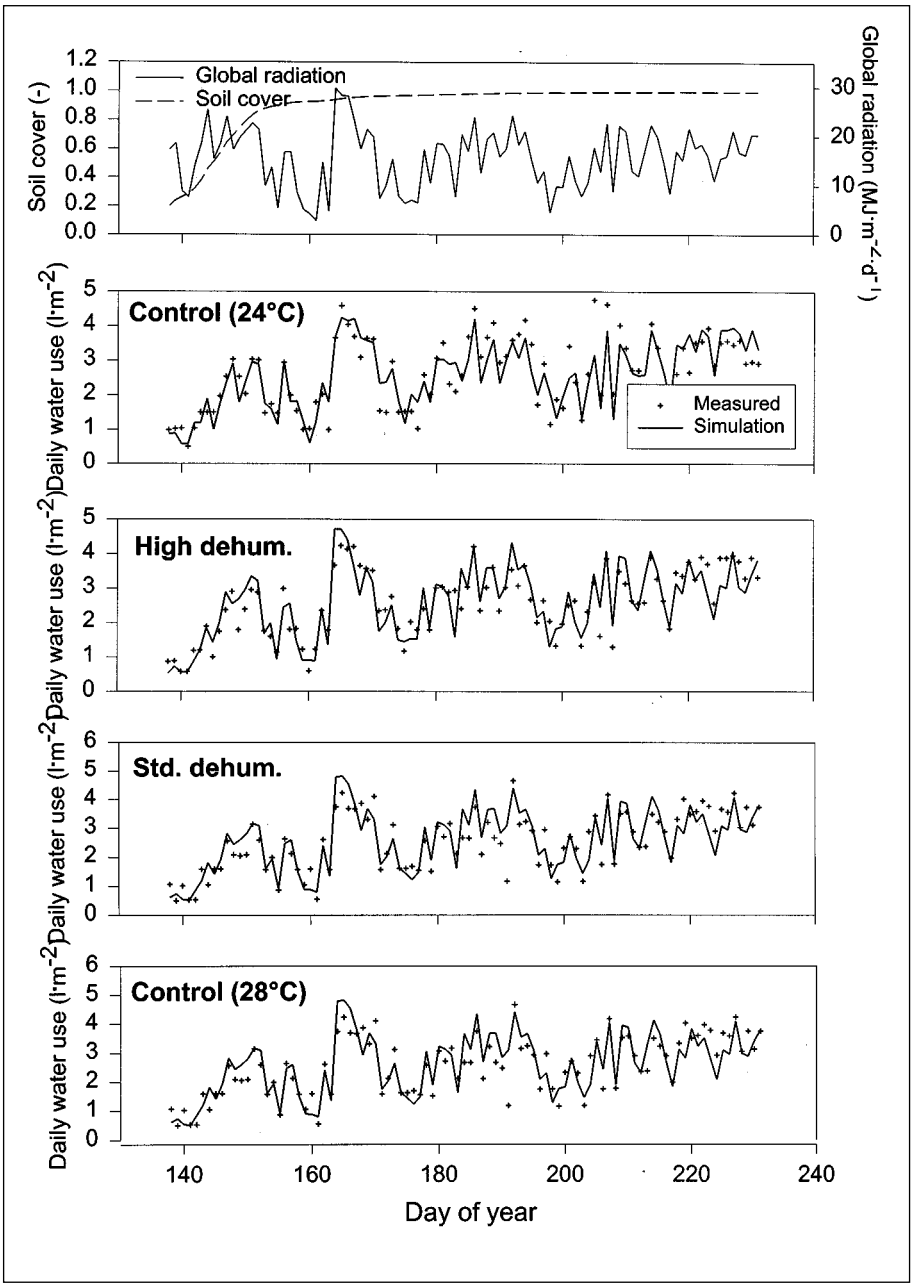


Fig. 3. Soil cover, global radiation as well as simulated and measured plant water use for cucumber crops grown 1988 in greenhouses with 4 different climatic treatments. (Data from FRICKE, 1992)
Bodenbedeckung, Globalstrahlung und simulierter sowie gemessener Wasserverbrauch von Gewächshausgurkenbeständen aus dem Jahr 1988 unter 4 unterschiedlichen Klimabehandlungen (Daten aus FRICKE, 1992).

Table 4. Slope, b, intercept, a, (± S.E.) and coefficient of determination of the linear regression between measured and calculated 1988 plant water use of cucumber crops. A Penman-Monteith based and multiple linear regression model parameterised from data of 1987 were used. Results are shown for the whole growth period and the period of full soil cover assumed to be reached 20 day after transplanting into greenhouse.
Steigung, b, Schnittpunkt, a, (± Standardfehler) und Bestimmheitsmaß der linearen Regression zwischen gemessenen und berechneten Wasserverbrauchsdaten der im Jahr 1988 gewachsenen Gewächshausgurkenbestände. (Berechnung mit einem Penman-Monteith basierten und einem multiplen linearen Regressionsmodell. Parameterisierung beider Modelle aus Wasserverbrauchsdaten des Jahres 1987. Ergebnisse getrennt für die gesamte Wachstumsperiode bei Nichtberücksichtigung der ersten 20 Tage).

Model	Data Included	slope	intercept	r^2
Multiple regression	From transplanting into greenhouse	0.52 (±0.03)	1.1 (±0.07)	0.46
	Starting 20 days after transplanting	0.78 (±0.03)	0.59 (±0.08)	0.70
Penman	From transplanting into greenhouse	0.86 (±0.02)	0.46 (±0.06)	0.75
	Starting 20 days after transplanting	0.83 (±0.03)	0.59 (±0.08)	0.71

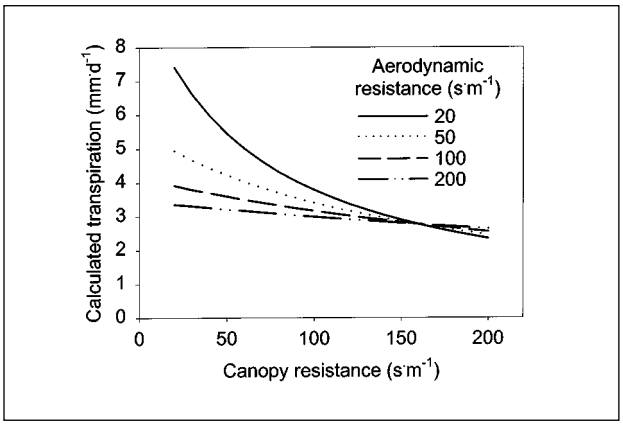


Fig. 4. Transpiration rates as calculated with the Penman-Monteith equation as a function of the canopy resistance for different values of the aerodynamic resistance. Assumed conditions: Global radiation: 10 MJ · m^{-2} · d^{-1}; saturation deficit: 7 hPa; Temperature: 20 °C.
Mit der Penman-Monteith Gleichung errechnete Transpirationsraten als Funktion des Bestandeswiderstandes für verschiedene Werte des aerodynamischen Widerstandes. Angenommene Bedingungen: Globalstrahlung: 10 MJ · m^{-2} · d^{-1}; Sättigungsdefizit: 7 hPa; Temperatur: 20 °C.

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