Infrared Thermometry for Early Detection of Drought Stress in *Chrysanthemum*

Margaretha Blom-Zandstra¹ and Klaas Metselaar

Plant Research International, P.O. Box 16, 6700 AA Wageningen, The Netherlands

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Abstract. Strict legislation on the release of water and nutrients into the subsoil exists in the Netherlands. Therefore, on-line monitoring and control systems are being developed to tune the supply of water and nutrients to the plants' demand for optimal control of production and reduction of system losses. In this context sensors and control systems are important tools. For *Chrysanthemum*, however, the effect of reduced irrigation on crop production is not well understood and more data from adequate sensors are required to establish critical soil moisture levels for an optimal crop water status and growth. We studied the effect of different soil water levels and soil desiccation in a climate chamber and under changing light intensities in a greenhouse to assess the critical soil moisture status for optimal growth of *Chrysanthemum* plants. Moreover, we studied the efficacy of infrared (IR) thermometry as a useful tool for on-line monitoring and control under the conditions of Dutch greenhouse horticulture. It is shown in this study that under moderate climate conditions plants start to suffer from water shortage when soil moisture potential pF reaches values below –32 kPa. Water status of the plant can very well be monitored on-line in a greenhouse as changes in leaf temperature due to water shortage can be detected by IR thermometry, especially at summer radiation levels. In the climate chamber however, leaf temperature did not respond to changes in soil water status, suggesting that the environmental settings of the climate chamber are unsuitable for these kind of experiments. In two of the three experiments at different levels of global radiation a change in leaf temperature is explained by a change in water regime. We conclude that regression analysis of high frequency on-line IR monitoring may be a useful tool for ex-post analyses of irrigation regimes at high light intensities, and may lead to interesting insights in crop responses.

Horticulture covers only 0.5% of the cultivated area in the Netherlands, but is responsible for 20% of the agricultural production value. Under the moderate climate conditions in Western Europe, the growers' aim at high productivity (especially during the winter season) is always limited by light intensity. High productivity can only be maintained by constantly adjusting production systems to market demand and reducing production costs. As water and nutrients are relatively cheap compared to supplementary lighting, and as the cost of excessive application is much lower than the cost of under-application, water and nutrients have often been supplied in excess, leaching large amounts into the environment. During the last decade, legislation in The Netherlands has become stricter and the quantity of water and nutrients released into the subsoil is being regulated. To meet state regulations and reduce loss of water and nutrients in soil grown crops, on-line monitoring and control systems are being developed to tune the supply of water and nutrients to the plants' demand. In their most sophisticated form, they are able to monitor the actual condition and buffering capacity of the soil–substrate as well as the condition of the crop. Systems are being developed in which these data are used

to predict crop variables. Based on predicted system responses, management actions are then suggested to optimally control production and reduce system losses. To date, monitoring systems have generally focused on substrate-based systems using tensiometers, or more recently, frequency domain sensors (Hilhorst, 1998; Hilhorst et al., 1996) to measure soil moisture characteristics. However, a number of food and ornamental crops are still soil grown for which the available monitoring systems are inadequate. The relationship between soil moisture status and crop production is indirect and subject to local differences.

The ornamental *Chrysanthemum* is still grown in a soil substrate, as plants are densely grown and frequently harvested, thus making a substrate-based system too costly. For *Chrysanthemum*, the work of Voogt et al. (2000) has led to a commercially applied irrigation system. This system combines measurements of soil moisture status and a plant growth model for *Chrysanthemum*. Whereas this was shown to reduce drain loads, the effect of reduced irrigation on crop growth and production is not well understood. To understand the effects of soil moisture status on chrysanthemum production requires a constant monitoring of the crop status and the establishment of a critical soil moisture status for optimal growth of *Chrysanthemum* plants. A single indicative value found by Voogt et al (2002) is a water level of 18% (w/w) in a fertigation experiment, but this is based on a final harvest only.

During crop growth water is needed for the maintenance of turgor and cooling of the leaves. The latter dominates water requirement. Transpiration is closely related to light intensity and has been well quantified for many crops. When the water supply becomes inadequate, stomata will close. A direct effect of stomatal closure is the reduction of transpiration, which leads to an increase in leaf temperature. Water shortage will reduce cell elongation, whereas stomatal closure will reduce the availability of carbon dioxide and thus the production of assimilates and growth. Monitoring the direct response of crops to water shortage by studying the increase of leaf temperature allows for early detection of water shortage.

Infrared (IR) thermometry is an accurate technique for measurements of leaf temperature. IR measurements of leaf temperature are robust, noninvasive, automated, and nondestructive. Therefore, they seem to be a promising sensing technique for the purpose of measuring crop status. Results of IR temperature measurements in *Chrysanthemum* have been presented by Langton et al. (2000), who suggested that wide angle infrared thermometers could be used for accurate vent and screen control at the canopy level.

The question arises whether this technique can be a useful tool for on-line monitoring and control of crop water status under the conditions of Dutch greenhouse horticulture. We examined the measurement of leaf temperature and whether its changes might be clear enough for early detection under the prevailing light conditions in the Netherlands. The effect of different water supplies on the leaf temperature and growth characteristics was studied in a climate chamber under constant environmental conditions. Moreover, the effect of soil desiccation under changing light intensities in a greenhouse was analyzed to assess the critical soil moisture status for optimal growth of chrysanthemum plants.

Materials and Methods

Experiments were performed at different levels from small-scale in a climate room (Experiment I) via semi practical scale in a greenhouse (Experiment II) up to practical scale in a commercial greenhouse (Experiment III).

Plant growth conditions. In Experiments I and II, 25-d-old rooted cuttings of *Chrysanthemum dendranthema* 'Reagan Sunny' were planted in Mitscherlich pots (enamelled pots, Ø = 20 cm, h = 22 cm) filled with sandy soil in agreement with standard production practice and covered with gravel (Ø = 0.5 mm; thickness of the layer: about 1 cm) to minimize evaporation. Control pots with gravel and without plants were added to evaluate the effectiveness of the gravel. Soil characteristics were according to de Bakker (1979) a sandy, silicious, mesic Typic Humaquept with 3% to 4% organic matter, 16% to 30% loam and a median sand fraction of 160 µm.

Plants were supplied with nutrient solution containing 12 ppm N. Total nutrient composition was 3.73 mM Ca(NO₃)₂, 4.40 mM

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¹To whom reprint requests should be addressed; e-mail greet.blom@wur.nl.

KNO₃, 0.97 mM KH₂PO₄, 1.92 mM MgSO₄, 0.89 mM K₂SO₄, trace elements, and Fe-EDTA (Steiner, 1968).

In Experiment I cuttings were then grown in a growth chamber at 18 ± 0.5 °C, 70% RH and a light intensity of 150 μmol·m⁻²·s⁻¹ (corresponding to 35 W·m⁻² solar radiation). Plants were grown at three different soil water levels: 19%, 14%, and 10% (by weight). A 16-h photoperiod was maintained for 4 weeks followed by a photoperiod of 12 h to induce flowering. Plants were harvested after 27, 35, 42, and 49 d.

In Experiment II cuttings were grown in a greenhouse from 1 May until 17 July at two soil water levels: 19% and 10% (by weight). Plants were protected against sunlight with a screen for 4 d. Photoperiod was artificially extended to 16 h. Mean day and night temperatures were 20 and 18 °C, respectively, with a mean relative humidity was 70%.

Water loss due to transpiration in Experiments I and II was measured by weighing the pots every 2 d, or daily (when plants were full grown) and tap water was added to a constant soil moisture content. The total water use was summed over time. The following growth characteristics were measured at harvest: stem length, number of leaves, leaf area, shoot fresh weight and dry weight (g), and leaf fresh and dry weight (g).

In Experiment III plants of *Chrysanthemum Dendranthema* 'Reagan Sunny' were grown in a greenhouse (net floor area = 204 m²) in soil composed of moderate humic sand, 2.4% to 4.0% organic matter, density 0.9 to 1.2 kg·dm⁻³.

The plants were grown on a lysimeter (Ø = 1 m²) and data on water use were recorded every minute. Plant height was measured as an indicator of plant growth. In the first 3 weeks plants were watered four times daily with DAN rotating sprinklers (Type 8991; REVAHO, Maasland, the Netherlands). In the following period, the crop was drip irrigated for 4 weeks on a per-demand dependent basis, based on a dynamic growth model (Voogt et al. 2000) with a setpoint of 200 mL·m⁻², after which the drip irrigation was stopped, and a period of plant desiccation started. Drought stress was imposed until the end of the experiment. In total data are available for 24 d in August, and 27 d in November.

Leaf temperature measurement. In Experiments I and II, leaf temperature was periodically measured with a steady-state porometer (LI-1600; LI-OR, Inc.). In Experiment III leaf temperature was measured each minute by an IR radiation thermometer (KT 17; Heimann, Wiesbaden, Germany) suspended 1 m above the crop (measured area radius: about 1 m) and stored on the computer. The canopy covered the soil completely.

Water retention characteristics. Water retention characteristics of the sandy soil used in the Experiments I and II were analyzed by measuring soil water content as a function of matric pressure following the standards (NEN-5786, 1991). Soil was placed on a porous plate connected to a burette to apply suction to an equivalent water column depth of -200 cm. In

the unsaturated zone water characteristics were determined according to this suction method (Stolte, 1997).

Theory. For agronomic use the Food and Agricultural Organisation of the United Nations (Allen et al., 1998) has defined a reference approach to calculate potential evapotranspiration. In this approach evapotranspiration is calculated for a reference surface and then modified to account for each crop and each stage of growth. To analyze temperature differences in terms of a similarly defined standard equation, the evapotranspiration equation can be rewritten (e.g., Jackson et al., 1981) in terms of the crop-environment temperature difference:

$$T_c - T_g = \frac{r_s}{\rho_a c_p} (R_n - G) \left(1 - \frac{\Delta}{\Delta + \gamma \left(1 + \frac{r_s}{c_p} \right)} \right) - \frac{(e_s - e_a)}{\Delta + \gamma \left(1 + \frac{r_s}{c_p} \right)}$$

where T_c = canopy temperature [°C], T_g = greenhouse temperature [°C], r_a = aerodynamic resistance [s·m⁻¹], ρ_a = mean air density at constant pressure [kg·m⁻³], c_p = specific heat of air [MJ·kg⁻¹·°C⁻¹], R_n = net radiation [MJ·m⁻²·s⁻¹], G = soil heat flux density [MJ·m⁻²·s⁻¹], Δ = slope of the saturated vapor pressure-temperature relationship [kPa·°C⁻¹], γ = psychrometric constant [kPa·°C⁻¹], r_s = (bulk) surface resistance [s·m⁻¹], e_s = saturation vapor pressure [kPa], and e_a = actual vapor pressure [kPa].

Based on this equation (under a number of assumptions discussed below), canopy temperature T_c can be estimated as a function of greenhouse temperature T_g , global radiation R_0 , and surface resistance r_s as $T_c = T_g + aR_0(1 + br_s)$.

Assuming T_g to be a linear function of radiation R_0 ($T_g = d + cR_0$) yields an equation which is linear in radiation, and in surface resistance, but contains the radiation-resistance interaction term $R_0 r_s$: $T_c = d' + (a + c)R_0 + abR_0 r_s$.

In well-watered (nonstressed) conditions surface resistance r_s decreases with radiation until a minimum value is reached which corresponds to the bulk surface resistance of a maximally transpiring canopy (fully opened stomata, e.g., Grossnickle and Russell, 1991; Kuiper, 1961; Jarvis and Davies, 1998; Losch et al., 1992; Stanghellini, 1987). Assuming r_s to be inversely proportional to R_0 as suggested, e.g., by the analysis of Jarvis and Davies (1998) the interaction term $R_0 r_s$ could become constant in well watered conditions, yielding a linear function between crop temperature and global radiation, or alternatively, a quadratic polynomial with a nonsignificant quadratic term.

In stressed conditions surface resistance increases with radiation (stomata are closing, transpiration flux is decreasing; Mott and Parkhurst, 1991), until a maximum value is reached. An analysis combining these effects is presented by Jarvis and Davies (1998) in terms of photosynthesis (proportional to global radiation) and transpiration flux. If, in a stressed condition, r_s increases linearly with R_0 , the interaction term $R_0 r_s$ becomes positively quadratic, yielding a quadratic polynomial relation between canopy temperature and global radiation.

Based on this discussion, the analysis of

canopy temperature vs. global radiation data would need to be based on a polynomial relationship with a linear and a quadratic term. We would expect specific combinations of linear and quadratic terms to occur in specific conditions. In case of a well-watered crop we would expect a linear relationship. In case of moisture stress we would expect both the linear and the quadratic coefficient to be positive.

This equation is based on a number of assumptions.

1) The net incoming radiation flux ($R_n - G$) is proportional to global radiation R_0 . This assumption is required due the lack of available data. The assumption can be justified on the basis of empirical equations to calculate net longwave radiation [e.g., Allen et al., 1998], which estimate net outgoing longwave flux on the basis of environmental air temperature) and assumption 3 (below). As an additional justification we offer the observation by Stanghellini (1987) that latent heat in greenhouse conditions can be estimated as a linear function of global radiation.

2) The crop-environment temperature difference is largely determined by radiation and crop stomatal resistance, with the latter having a very small effect. This is a special property of greenhouses (Jones and Tardieu, 1998).

3) The relation between environmental temperature and global radiation is approximately linear (no heating). For this assumption to hold, partitioning of radiation energy over evaporation and sensible heat (i.e., the Bowen ratio) has to be constant over the period considered (i.e., 1 d).

Statistical analyses. In the Experiments I and II plants were randomized in block design with five replicates of each treatment. Differences between treatments were determined by analyses of variance (ANOVA) using Genstat 5 (Rothamsted Experimental Station, Harpenden, U.K.). In Experiment III, based on the above described theory, a second-order polynomial using radiation as the explanatory variable was fitted to the available crop temperature-radiation data on a day-to-day basis. We focus on the descriptive relation between crop temperature and radiation for each day in the dataset. The large number of data—due to the high measurement frequency—should allow to establish the parameters with a relatively small standard deviation. We test whether the regression coefficients are significantly different from 0, using a *t* test at *p* = 0.05.

Results

Growth responses of *Chrysanthemum* to different water supplies. Growth of *Chrysanthemum* in time was followed in a climate room at constant temperature and light intensity by periodically measuring leaf temperature. Leaf temperature did not differ between different water supplies (i.e., 18.9 to 19.0 °C with a standard deviation in the range of 0.34 to 0.46). Table 1 shows growth characteristics at different water supply treatments for all harvests. Almost all growth characteristics differed significantly between the water treatments, which differed from 19% to 14% moisture content

Table 1. Growth characteristics of *Chrysanthemum* plants grown at three different water regimes.

Growth variable	Soil moisture content			SED	Significance
	19%	14%	10%		
Shoot fresh weight (g)	198.2	173.8	83.4	4.31	***
Shoot dry weight (g)	27.45	25.21	13.43	0.77	***
Stem fresh weight (g)	84.0	75.0	35.6	2.3	***
Stem dry weight (g)	13.48	12.56	6.54	0.46	***
Leaf fresh weight (g)	114.23	98.8	47.82	2.20	***
Leaf dry weight (g)	13.97	12.65	6.89	0.32	***
Stem length (cm)	59.14	58.25	53.83	0.96	***
Number of leaves	32.03	31.33	29.12	0.64	***
Total leaf area (cm ²)	3361	2949	1420	69	***
Water demand per plant per day (mL/plant/day)	113.9	97.4	53.3	2.8	***

***Significant at $P < 0.001$.

Fig. 1. Water retention characteristics of a sandy soil measured by water extraction (○) and water supply (■). Error bars are standard errors of the mean.

treatments between 14% and 10%, suggesting that plants severely suffered from water stress below 14%. Stem length was only significantly reduced when the water content of the soil was below 14% and it can be calculated that leaf number per stem length was not significantly different between different water supplies. For growers stem length is an important parameter

on a per weight basis. Differences in growth characteristics were more profound in moisture

as it determines flowers' prices.

The relationship between soil water content

and pF values for the soil type used in this experiment is studied. The pF is defined as $\log[\text{absolute value of the suction in cm water column}]$ and -10 cm (i.e., pF 1) corresponds to -1 kPa matric potential. The result is shown in Fig. 1. Thus 14% water content corresponds to a pF value of 2.5 (-32 kPa). This indicates that *Chrysanthemum* plants start to suffer from water shortage at values above pF 2.5. The soil shows a substantial hysteresis between 2.0 and 0.45. At lower water volume fraction no hysteresis occurs. However, the hysteresis was no complication during the experiments in the climate chamber as water content in the pots was kept constant.

Water use. The relationship between plant growth characteristics and water use are presented in Fig. 2. Plant appearance was clearly affected by the water status of the soil, but the ratios were not: low water supply reduced stem length growth substantially. However, total water use was independent of shoot weight (Fig. 2A). So, it can be suggested that the available water dictates plant growth response. Stem length and total water use varied with water treatment during growth (Fig. 2B) as did water use per individual leaf (Fig. 2C). In contrast, water use per unit leaf area was independent of water supply (Fig. 2D).

Fig. 2. Relationship between different plant growth characteristics and total water use (mL) of chrysanthemum plants grown at soil moisture contents (□ 19%, △ 14%, ○ 10%) and different harvest times (◆ 27, ■ 35, ▲ 42, ● 49 d) in a climate chamber. (A) Shoot fresh weight production (g); (B) stem length (cm); (C) amount of leaves, and (D) leaf area (cm²). Error bars are standard errors of the mean.

It is clear that the morphological plant characteristics (i.e., stem length, amount of leaves) reflect the degree to which the environment was water stressed. In contrast, ratios such as water use per leaf area are more conservative.

Water use at changing light intensity. The above experiment was repeated in a small greenhouse from May (day 150) to July (day 200) in Experiment II. Light intensity (as a fraction (0.5) of global radiation) was substantially higher and changed constantly during the course of the experiment. Under these circumstances water supply considerably affected water use per unit leaf area (Fig. 3). In contrast to the results from the growth chamber experiment (Fig. 2A–D), water use per unit leaf area was significantly lower at low water supply (10%) than at fully water supply (19%) and was accompanied by a small but significant ($P = 0.10$) increase in leaf temperature (Fig. 4). Apparently, under higher and changing light intensity, water use per leaf area and leaf temperature are sensitive parameters for water

availability and may be used for monitoring and control purposes during growth.

Leaf temperature as controlling factor. To study leaf temperature in more detail, plants were grown in a greenhouse (Experiment III) and subjected to changing global radiation levels and to desiccation during the growing season. Figure 5 shows the daily course of transpiration, radiation and temperature difference (ΔT) between leaf and greenhouse on different days. The results represent two days in summer under circumstances of high light intensity and differing in water status of the plants [1 Aug., well watered (Fig. 5A) and 24 Aug., desiccated (Fig. 5B)]. Also shown are the results of two days in fall under circumstances of low global radiation and also differing in water status of the plants [4 Nov., well watered (Fig. 5C) and 24 Nov., desiccated (Fig. 5D)]. The transpiration pattern closely followed the pattern of the global radiation, independent of the moisture status of the soil. However, the daily pattern of ΔT differed, while it did not change during

the day at 1 Aug. (Fig. 5A), it increased substantially at 24 Aug. (Fig. 5B), when the soil had been dried out. At lower global radiation in fall the differences were less pronounced: at 24 Nov. (Fig. 5D) leaf temperature also increased with light intensity at dry conditions, but the differences with well watered conditions (Fig. 5C) were much less pronounced. At these low global radiation levels leaf temperature only slightly exceeded greenhouse temperature. So, the effect of desiccation on daily ΔT strongly depended on the season in which the plants grew. Average daytime ΔT increased over the moisture stressed period, both in August and November (Fig. 6A and B).

Global radiation had an important effect on the change of leaf temperature during desiccation of the plants. Figure 7 shows leaf temperature as a function of global radiation at different degrees of desiccation in August (Fig. 7A) and November (Fig. 7B).

Derived from theory the relation between canopy temperature and global radiation is approximated by $T_c = c + bR_0 + aR_0^2$, in which T_c = leaf temperature ($^{\circ}\text{C}$), R_0 = global radiation ($\text{W}\cdot\text{m}^{-2}$), and a , b , and c are regression coefficients.

A day-to-day analysis of measurements on a per minute frequency shows changes in the shape of the quadratic function, i.e., its regression coefficients. In August we observed an increase in the coefficients of the linear term (Fig. 8A) and a sign change (from positive to negative) in the coefficients of the quadratic term (Fig. 8B).

In November we observed high values for the coefficient of the linear term on the four final days (Fig. 8C; and negative values in that same period (Fig. 8D). In addition to the theory we observed a positive linear coefficient and a negative quadratic coefficient at the end of the imposed drought period.

Discussion

Critical water supply. In a climate chamber with *Chrysanthemum* at about $35 \text{ W}\cdot\text{m}^{-2}$ PAR under constant environmental conditions (Experiment I), plants started to severely suffer from water shortage when the soil water status dropped below 14% by weight (see Table I). This corresponds to a pF value of 2.5 ($= -32 \text{ kPa}$). Water supply allowing pF values below this critical level results in reduced growth and increased stem length. Water use per plant or leaf area is also reduced. In contrast to Experiments II and III we did not find any effect on leaf temperature. Moreover, small but significant changes in leaf temperature were observed at global radiation levels of $88 \text{ W}\cdot\text{m}^{-2}$ (average instantaneous value, Experiment III, November). The lack of change of leaf temperature in the climate chamber setup raises the question whether the physiological responses of *Chrysanthemum* in the environmental settings of the climate chamber and a greenhouse are sufficiently similar to advocate the use of this moisture criterion for practical application. These results lead us to suspect that there is a critical environmental regime below which stomatal regulation of transpiration is not

Fig. 3. Water use per unit leaf area ($\text{mL}\cdot\text{cm}^{-2}$) during the growing season of chrysanthemum plants in a greenhouse. For growing details, see Materials and Methods. Error bars are standard errors of the mean.

Fig. 4. Leaf temperature ($^{\circ}\text{C}$) during the growing season of chrysanthemum plants in a greenhouse. For growing details, see Materials and Methods. Error bars are standard errors of the mean.

Fig. 5. Examples of the daily course of elevation of leaf temperature; ΔT = leaf–environmental temperature ($^{\circ}\text{C}$), crop transpiration ($\text{g H}_2\text{O}$), and radiation ($\text{W}\cdot\text{m}^{-2}$) of chrysanthemum grown in a lysimeter in a greenhouse. (A) 1 Aug., well watered; (B) 24 Aug., desiccated; (C) 4 Nov., well watered, and (D) 24 Nov., desiccated.

Fig. 6. Examples of the relationship between crop canopy temperature ($^{\circ}\text{C}$) and global radiation ($\text{W}\cdot\text{m}^{-2}$) at different levels of desiccation. (A) 1 Aug., (B) 24 Aug., (C) 4 Nov., (D) 24 Nov. All parameter estimates for both 1 and 24 of Aug. are significant; for November the parameter estimates for 4 Nov. are significant; those for 24 Nov. are nonsignificant. Significance at $P = 0.05$, using a t test.

active or even deteriorates, and crops adapt to moisture stress through phenological plasticity only. At present this must remain an hypothesis, which has to be studied in more detail.

Crop water status monitoring. Infrared thermometry did not show any significant differences in leaf temperature between moisture treatments in the climate chamber settings of Experiment I (constant temperature of 18 °C,

radiation intensity of 35 W·m⁻² PAR). Under summer conditions in the greenhouse, the difference in leaf temperature between two moisture treatments was maximally 0.25 °C at a 9% difference in moisture content. In Experiment III the daytime average crop–environment temperature difference increased in time after irrigation stopped, and the crop became warmer than its environment.

Experiment II suggests that the method is not very sensitive under these experimental conditions. A relatively large difference in moisture content of 9% leads to a difference of 0.25 °C between treatments. Experiment III suggests that trends in crop temperature are perhaps more interesting as a diagnostic of water stress with two options: one is the daytime average crop–greenhouse difference, and its

Fig. 7. Changes in the daylight average temperature difference (°C = ΔT measured as leaf temperature – environmental temperature) as a function of time for August (A) and November (B). Presented is the mean and its 95% confidence interval, calculated as a daytime average.

Fig. 8. Linear (A and C) and quadratic (B and D) parameter values of a regression analysis using a quadratic polynomial between crop temperature and radiation. Results (if parameter estimates not significantly different from 0, plotted using ■ with 95% confidence interval, else plotted as ▲) are presented for both August (A and B) and November (C and D). The proposed use of these regression coefficients is as indicators for soil moisture stress.

Table 2. Diagnostic table to assess moisture stress.

	Linear coefficient		
	Negative	Nonsignificant	Positive
Quadratic coefficient positive	Further analysis required	Stressed	Stressed
Quadratic coefficient nonsignificant	No stress	Nonsignificant	Stressed
Quadratic coefficient negative	Not observed	Not observed	Severely stressed

development in time; the other is an analysis of the relation between crop temperature and global radiation.

The theoretical analysis presented in this paper suggests that leaf temperature can be described by a quadratic function of radiation. The linear term reflects a nonmoisture limited response of the crop to radiation; the quadratic term reflects interaction between crop resistance and radiation. In stressed situations one would expect the radiation-resistance interaction term to become more important, leading to significant positive values of the regression coefficient. Whereas this behaviour can be recognized in the early part of the stress period, results showed that in the final part of the moisture stress period, especially under summer conditions, the quadratic coefficients become negative. One possible explanation is that at high radiation levels and high moisture stress crop resistance becomes constant at a maximal value (all stomata closed). This causes the resistance-radiation interaction term to disappear, leading again to a linear response of crop temperature to radiation at high radiation levels, in a heavily stressed situation. This behaviour could be empirically described by the rising branch of a parabola opening downwards. To find crop temperature decreasing with radiation in a heavily stressed situation would be surprising, and would have to be attributed to causes other than the described mechanism, e.g., crop cooling by forced ventilation of the greenhouse or by water misting nozzles.

The analysis of the relation between crop temperature and global radiation in terms of the coefficients of a quadratic polynomial regression suggests the following diagnostic table to assess moisture stress based on daily crop temperature data measured on a per minute basis (Table 2).

Based on the results of this analysis we expect this procedure to be successful in summer, and less so in winter.

To summarize the effect of reduced water supply on crop water status of *Chrysanthemum* and possibilities for control we found the following.

- 1) Under moderate climate circumstances the critical soil water status for *Chrysanthemum* can be clearly identified. The growth characteristics and water use show that plants start to suffer from water shortage when soil pF reaches values above 2.5.
- 2) Water status of the plant can be monitored on-line as changes of leaf temperature due to water shortage can be detected by IR thermometry, especially at summer radiation levels.
- 3) High frequency on-line monitoring of crop IR temperature may be a useful tool for ex-post analysis of irrigation regimes at higher light intensities, as the response in canopy temperatures to the daily course in radiation is possibly specific for a specific moisture stress situation. In addition to theoretical considerations which would lead us to expect positive linear and quadratic coefficients in a stressed period, we observe a positive linear coefficient and a negative quadratic coefficient in the most heavily stressed period. Further experimentation to elucidate this phenomenon is required.

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