Management of Greenhouse Crop Transpiration: the Way Forward

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Abstract

The importance of management of greenhouse crop transpiration increases, being part of both the water and energy balance. A simulation model for crop transpiration can serve as a soft-sensor in an early warning system for the grower, and is an essential component of an energy model for a greenhouse with a crop. Published data on model validation of crop transpiration under commercial settings are scarce. In an effort to develop a model-based soft-sensor for crop transpiration, continuous and instantaneous rates of crop transpiration were obtained over a large part of 2006 from a tomato grower using a weighing gutter. The wide variation in environmental conditions caused similarly wide variation in crop transpiration rates, both among and within days. This enabled broad model validation. Validation gave over-estimation of crop transpiration, but parameters that relate the stomatal conductance to environmental conditions were successfully calibrated on the basis of total daily transpiration. Although seasonal calibration may in certain cases be sufficiently accurate to enable robust simulation of daily course of crop transpiration, a more robust approach is to calibrate for shorter time periods than an entire season. Robustness is a prerequisite for on-line management of the water and energy balances. Further data analysis can reveal structural patterns in the relations between model parameters and simulated transpiration. Built on this, on-line sensor information on transpiration can be used to continuously optimize the transpiration model, and increase its usefulness in information and early-warning systems.

INTRODUCTION

Crop transpiration is a process of both the water and the energy balance. Annual transpiration of a standard tomato crop accounts for 1558 MJ m^{-2}, approximately a third of the annual energy input (Elings et al., 2005). Transpiration management in closed greenhouses increases in importance, for a number of reasons. Reduced energy consumption is a prime focus of both growers and society as energy costs increase and fossil energy availability decreases. Optimum water management can contribute to reduction of energy input (Dieleman et al., 2006). Also, with the introduction of closed greenhouses it became necessary to manage relative air humidity in other ways than ventilation to the outside air (Bakker, 2006); the acquired knowledge is now also applied in semi-closed and regular greenhouses. The chances of outbreak of fungal diseases such as *Botrytis* that favour humid micro-climate conditions are taken seriously (Körner and Holst, 2005). Water uptake and distribution are key factors for mineral uptake and transport and hence the distribution among plant parts. Reduced water uptake will enhance problems such as Ca and Mg deficiency (Bakker, 1991b; Sonneveld, 1987). Also, crop water uptake influences the EC of the root environment, which has an effect on e.g. fruit quality of tomato fruits.

Management of crop transpiration relies on on-line or early warning facilities, and should provide the grower with crop management options for the (near) future. In most current greenhouses, a greenhouse model based on empirical relations generates set points for irrigation and sends these to a control unit (Fig. 1). Outdoor and greenhouse environmental conditions are taken into account. The control unit generates a fertigation regime, which eventually has an effect on crop transpiration, growth, production and product quality (although usually, sufficient water is applied). Importantly, there is no interaction between the crop and the greenhouse model that generates set points, which makes it impossible to account for the needs of the crop. This situation can be modified by introducing a number of additional elements (Fig. 1). Firstly, the greenhouse model based on empirical relations must be replaced by an explanatory greenhouse model that physically describes the energy flows in a greenhouse. Secondly, a crop model (preferably combined with a substrate model) must be introduced to describe the water and nutrient balance, including crop demand for water and nutrients. A simulation sub-model for crop transpiration is an essential component of a model dealing with the energy balance of a greenhouse holding a crop. The crop and the greenhouse models show overlap with regards to the transpiration sub-model: it is part of the water balance of the crop model, and part of the energy balance of the greenhouse model. Sensor information on crop transpiration is used, in combination with self-learning properties of the transpiration sub-model, to maintain the model's correspondence with the actual situation. The transpiration sub-model can serve as a soft-sensor to send an early warning to the grower in case a certain water management action is required. A parallel can be drawn with the management of the fertigation regime. In a demonstration project, it was shown that on the basis of crop demand for water and nutrients, fruit quality (fruit dry matter content) could be improved through an optimized fertigation regime, influencing the slab EC (unpublished data). Through this combination of elements, the needs of the crop can be taken into account, and early-warnings and management options can be generated.

Crop transpiration has been widely studied under both open-field conditions and in closed systems. Many are based on the Penman-Monteith equation (Monteith, 1965) that links the evaporative heat loss to LAI, radiation, vapour pressure deficit and the canopy conductance for water vapour. The effect of radiation, vapour pressure deficit, air CO_2 concentration and air temperature on stomatal conductance has for greenhouse crops been described and parameterized by Stanghellini (1987), Bakker (1991a), and Nederhoff and de Graaf (1993). Others use linear regressions to link transpiration directly to environmental conditions (De Graaf, 1981; Baptista et al., 2005). The Intkam model for growth and development of greenhouse crops (Marcelis et al., 2000) incorporates a water balance (Gijzen, 1994). The model simulates the instantaneous rate of potential crop transpiration under the influence of radiation, air temperature, vapour pressure deficit, CO_2, and wind speed. In addition, potential water uptake rate as a consequence of dry matter increase is computed. Jointly, the two rates compose the instantaneous rate of potential water uptake by the root system. Simulated water uptake rate is under most circumstances equal to potential water uptake rate; and is lower only if water availability is insufficient, which can be simulated by combining the crop model with a substrate model (Elings et al., 2004).

Published detailed observations on crop transpiration by commercially grown crops are relatively scarce, and mostly restricted to a limited period of time. Model validation on the basis of data obtained under experimental conditions was not always consistent (unpublished data). The availability of detailed full-season observations on crop transpiration of tomato crop enables the evaluation of the performance of the Intkam transpiration model.

MATERIALS AND METHODS

Crop transpiration rates of a commercially grown tomato (*Lycopersicon esculentum*) crop were observed during the 2006 growing season with a ProDrain weighing gutter (HortiMax, Pijnacker, The Netherlands) at a greenhouse farm in The Netherlands. The weighing gutter produced instantaneous crop transpiration rates at an interval of 5 min. Periods with unreliable data were excluded from the data set, and single unreliable and missing data were replaced by estimates. A detailed description of the weighing gutter is given in de Graaf et al. (2004).

Average outside global radiation (R_{glob}, J m^{-2} s^{-1}), outside air temperature (T_{out}, ^oC), inside air temperature (T_{in}, ^oC), heating pipe temperature (T_{pipe}, ^oC), inside CO_2 concentration (ppm), inside relative air humidity (RH, %), and screen closure (%) were recorded at 5 min. intervals. Inside air vapour pressure deficit (VPD_{air}, kPa) was computed from T_{in} and RH. Climate data were available from day 62 onwards.

Development of the leaf area index (LAI, m^2 m^{-2}) was estimated with the Intkam simulation model (Marcelis et al., 2000). Representative climate data were used between planting (December 1st) and first available climate data. It was assumed that the crop was planted at a density of 3.76 shoots m^{-2}. It was also assumed that first leaves were picked two weeks before first truss harvest, and that all leaves below a truss were removed at the moment of its harvest. Simulated truss harvest and leaf removal occurred approximately once a week, resulting in a zig-zag simulated LAI time-pattern. As the exact moments of truss harvest and LAI reduction due to leaf removal are difficult to simulate, a smoothed LAI-curve over time was developed and used in computation of crop transpiration.

Crop transpiration was simulated with the transpiration module extracted from the Intkam model. It requires time, R_{glob}, the greenhouse azimuth, light transmission for diffuse radiation by the greenhouse cover and construction (set at 75%), and LAI as input. Accounting for solar elevation and fraction overcast sky, the module computes direct and diffuse components of PAR and NIR inside the greenhouse at the top of the canopy. It assumes light extinction coefficients of 0.78 and 0.38 for PAR and NIR, respectively. Instantaneous leaf transpiration rates at five canopy depths were computed from intercepted direct and diffuse radiation, for sunlit and shaded leaves. Instantaneous crop transpiration rate is computed with a 5-point Gaussian integration over canopy depth (Goudriaan, 1986). This Intkam stand-alone transpiration sub-model does not incorporate effects of other physiological process on transpiration, and assumes ample water supply, resulting in the absence of an effect of crop water status on transpiration. Feed-forward or feed-back effects were assumed absent.

Stomatal conductance G_s (m s^{-1}) was computed for the day and night period separately (Bakker, 1991a), through an iteration of $VPD_{leaf-air}$ and leaf temperature (T_{leaf}), incorporating environmental effects with equations given by Stanghellini (1987), Bakker (1991a), and Nederhoff and de Graaff (1993). Default parameter values had been determined previously on the basis of data obtained under commercial and experimental conditions (unpublished data). During the light period, only R_{abs} and VPD_{air} have an effect on G_s, whereas in the dark period, only VPD_{air} has an effect. The effects of CO_2 concentration and T_{in} did not further explain variation in canopy transpiration. Adapting the radiation-related parameters leads to changes in G_s and transpiration rate only at relatively low radiation levels, whereas an adapted VPD-related parameter are effective at all radiation levels. The transpiration model was first validated with default parameters, which were subsequently calibrated on the basis of values for total daily transpiration (TR_{daily}) over the entire season. It was not attempted to calibrate on a daily basis.

RESULTS

LAI and Radiation

Simulated LAI started at 0.25 m^2 m^{-2} at planting, increased to 4.3 m^2 m^{-2} at the beginning of May, and decreased to 3 m^2 m^{-2} at the end of the growing season. The average simulated LAI reduction associated with leaf removal at truss harvest was 11%. Simulation showed that on a seasonal basis, 45% of the total global radiation was absorbed by the crop (R_{abs}), of which 62% was absorbed as photosynthetically active radiation (PAR_{abs}, 28% of R_{glob}). R_{abs} is driving transpiration, while PAR_{abs} is driving photosynthesis.

The relation between $R_{abs,daily}$ and observed TR_{daily} was linear, with a slope of 0.58 (Fig. 2). The positive relation between daily average VPD_{air} and observed TR_{daily} does not show such a clear linear trend.

Model Validation

Simulation of transpiration with the default parameters resulted, on average, in over-estimation of total TR_{daily} by 50%, with a fairly stable the simulation error ($r^2_{linear\ fit}$ = 0.91, Fig. 3). $R_{abs,daily}$ explained 90% of the variation in observed TR_{daily} and 92% of the variation in simulated TR_{daily}.

Model Calibration

A greenhouse transmission of 75% had been assumed, which is a realistic value for modern greenhouses. Lower transmissions up to 65% resulted in only minor reduction of TR_{daily}, and therefore, the over-estimation TR_{daily} can not be attributed to incorrectly assumed values for greenhouse transmission.

Calibration gave better results if the stomatal response to VPD at daytime was adjusted, than if the response to radiation was adjusted, presumably because the former modification is effective at all radiation levels, while the latter modification is only effective at radiation levels below approximately 250 J m^{-2} s^{-1}. Combined with reductions of $G_{s,l,max}$ and $G_{s,d,max}$, this resulted overall in acceptable simulation of daily total transpiration (Fig. 3).

One unavoidable source of variation is the inaccuracy in simulated moments of LAI reduction as a consequence of frequent leaf harvests when trusses are harvested. The simulated LAI reduction is 11%, causing on average 7% reduction in simulated TR_{daily}.

There are time effects with regards to over- and under-estimation of TR_{daily}. Simulated values were over-estimated in the months of August to November, under-estimated in the months of March and July, and on the whole adequately simulated in the months of April-June. Over-estimation appears to be associated with late summer and autumn conditions, while spring and early summer months appear associated with under-estimation.

The relation between total daily absorbed radiation and the amount of transpiration per unit intercepted radiation (kg MJ^{-1}) was determined. The transpiration rate per unit intercepted radiation decreases as the amount of intercepted radiation increases, following the law of diminishing return: each additional unit of intercepted radiation results in a lower amount of transpired water. While the effect is most clear if data are generated on a theoretical basis, keeping all other conditions (time, LAI, temperature, VPD) constant, dynamic values of TR_{daily} show the same effect (Fig. 4). The ratio between transpiration and absorbed radiation at 12.5 MJ m^{-2} intercepted radiation levels is 0.35 kg MJ^{-1}.

The quality of within-day simulation of transpiration can be grossly arranged in a number of groups, or combinations thereof (Fig. 5):

- adequate simulation during the entire day, or during the day or night-time period;
- trends and changes are captured by the simulation model while the absolute simulated level is too high or too low;
- peaks or dips in transpiration are not captured;
- simulated transpiration does not reflect observations.

In Figure 5, a number of examples are given that reflect the variation in quality of within-day simulation of crop transpiration.

DISCUSSION

Model validation gave an over-estimation of total daily transpiration, although data scatter was relatively low. The response of stomatal conductance to environmental conditions could, on a seasonal basis, be calibrated such that daily transpiration was simulated accurately. Although seasonal calibration may in certain cases be sufficiently accurate to enable robust simulation of daily course of crop transpiration, a more robust approach is to calibrate for shorter time periods (this is how literature data have often been derived) than an entire season. Robustness is a prerequisite for on-line management of the water and energy balances. It can be realized in a self-learning environment: an on-line sensor obtains information on transpiration, based on a feed-back signal from the weighing gutter, and sends this to an optimization module that selects the best parameters for the transpiration model. This approach would also improve model performance on a short time scale, and provide growers with insight in crop behaviour in the course of a day. A similar on-line approach for the selection of the optimum fertigation regime has proven to be effective (Elings et al., 2004).

A valuable analytical step would be the further investigation of structures in the results of a sensitivity analysis: can variation in a specific parameter be associated with variation in crop transpiration during specific time periods, or under specific climatic conditions? The time effects with regards to over- and under-estimation of TR_{daily} could be an example. It would also be necessary to separately analyze day and night-time transpiration, to exclude variation in night-time transpiration as a source of error in the relation $R_{abs,daily}$ - TR_{daily}. This could increase our understanding of the stomatal response to environmental characters.

Information on, and management of, crop transpiration is increasing in importance. Early warning systems need a model that generates forecasts of transpiration. It appears that on-line model calibration in a self-learning environment increases model performance, therewith adding value to the information supply to growers.

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Figures

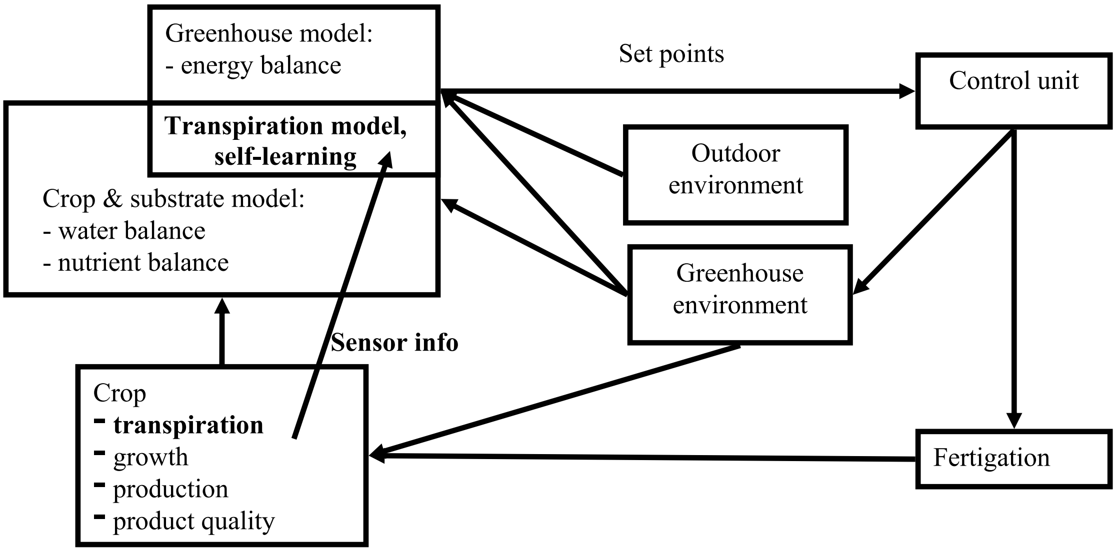

Fig. 1. Schematic overview of a transpiration management system, including a self-learning transpiration model that utilizes sensor information on transpiration.

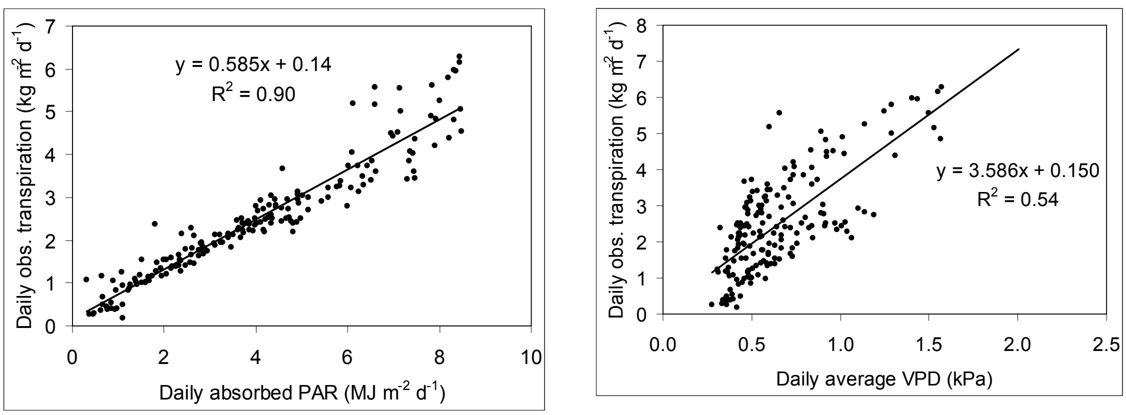

Fig. 2. Relations between observed daily absorbed radiation (left) and observed daily average VPD_{air} (right), and observed total daily transpiration.

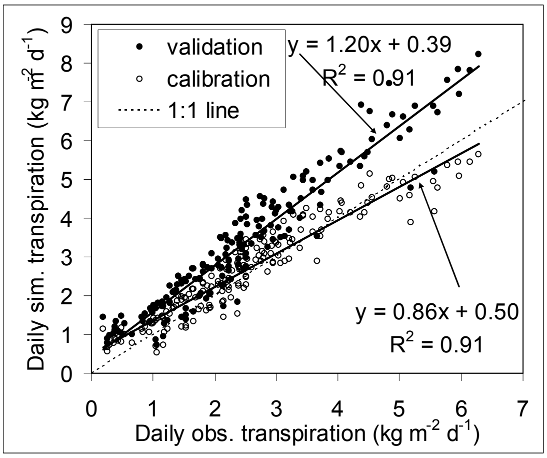

Fig. 3. Daily observed and simulated crop transpiration, at validation, and after calibration.

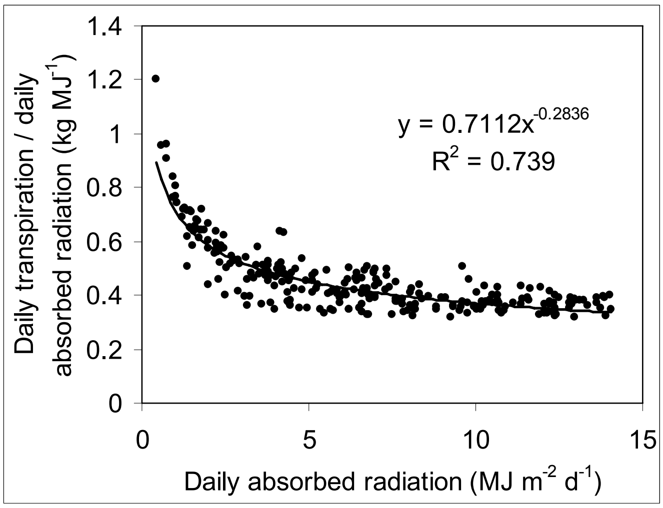

Fig. 4. Relation between daily absorbed radiation and the amount of daily transpiration per unit absorbed radiation (points: observations; line: trendline).

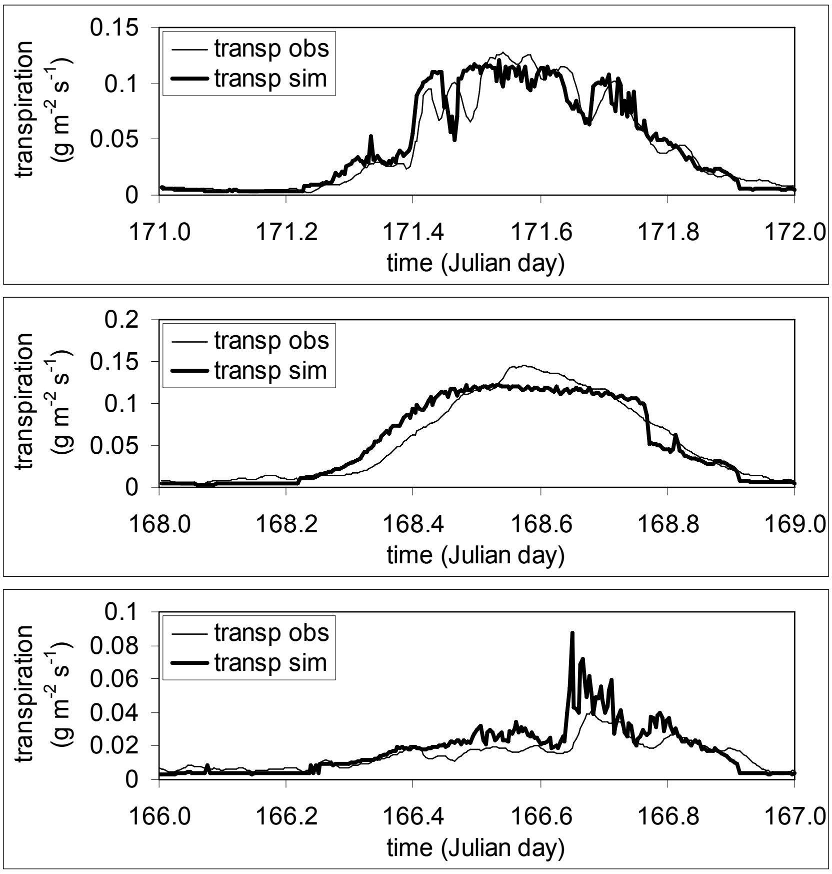

Fig. 5. Three examples of daily courses of observed and simulated transpiration rates. Top: observed variation well-captured in simulation; middle: observed peak under-estimated in simulation; bottom: observed transpiration does not show peak as simulation does (associated with peak in radiation).