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Remote and Real-Time Sensing of Transpiration and Stomatal Resistance Based on Infrared Thermometry

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Abstract
A remote method was developed for monitoring leaf transpiration rate and stomatal resistance on a real-time basis. The method utilized leaf temperatures measured with an infrared radiometer as an integral input for a model to compute those parameters. The model was based on the energy balance of a plant leaf, accounting for moisture transfer processes in the stomata and boundary layer. Remotely determined transpiration rates and stomatal resistance in maize leaves in the field were compared with those measured with a steady-state porometer. The corresponding values obtained from the two methods were linearly correlated, while no specific relationship was found between leaf-air temperature differential and stomatal resistance or transpiration. The porometer transpiration rates were slightly higher than those obtained by the "remote" method with a correlation coefficient of 0.93**, probably because the air in the porometer cuvette was drier consistently than the ambient air. The stomatal resistance values from the two methods fell on the 1:1 line with a high correlation coefficient (0.96**), suggesting that the "remote" method produce excellent estimates of actual stomatal resistance.

Discipline: Agro-meteorology
Additional key words: leaf temperature, model, monitoring

Introduction

The infrared thermometry has great advantages for inferring the crop water status, being non-destructive, real-time and quantitative[18,21]. In the arid and semi-arid regions, a linear relationship exists between canopy–air temperature differential and air vapor pressure deficit[1,4] or extractable water remaining in soils[9,16]. Inoue[6,12] showed that the thermal imagery was effective for comparing physiological differences in crop canopies. The temperature data alone, however, can not necessarily be the absolute indicator of physiological status especially in case of non-imagery measurements, since the leaf temperature is influenced by micro-meteorological factors such as solar radiation[16]. The remotely-sensed leaf temperature can hence provide more meaningful and quantitative information when used as an input to stress-indices or biophysical models, although supplementary measurements such as air temperature and humidity are also required. Jackson and his co-workers[4,17] developed a useful index, CWSI (crop water stress index), using the data on canopy temperature as well as on air temperature and humidity for evaluating a relative intensity of drought stress. The CWSI, however, takes no account of the changes in net radiation, nor windspeed as discussed by Jackson[18]. It is expected that absolute estimates of transpiration and/or stomatal resistance measured with a remote means may provide a useful base for physiological diagnosis and yield predictions.

With the purpose of monitoring transpiration rate and stomatal resistance of crop leaves, a remote and real-time method was developed. The model was based on the energy balance of a single leaf using infrared leaf temperature as one of the major inputs to the model[7,10,11,13]. The present paper attempts

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to review the results of the relevant studies to this subject.

Model description

The proposed model estimates leaf transpiration (Tr) and stomatal resistance (r_{sv}), using equations for energy balance of a plant leaf and for moisture exchange processes in the stomata and the boundary layer[7,11,18,19]. In pursuing those processes, the model takes into account the changes in solar radiation, windspeed and boundary layer resistance in an explicit way.

Tr can be described as a part of the energy balance of a leaf as follows:

$$\mathrm{Tr} = (R_n - H)/2\lambda\ , \quad \text{......} \quad (1)$$

where Tr is the mean one-sided value of leaf transpiration rate, λ is the latent heat of vaporization, R_n is net rediation, and division by 2 is required to obtain a one-sided Tr value. H is the rate of sensible heat transfer from both sides of the leaf to the ambient air; and it is expressed, based on the heat exchange process in the boundary layer, as follows:

$$H = 2\rho Cp(t_l - t_a)/r_{ah}\ , \quad \text{......} \quad (2)$$

where ρ is the density of air, Cp is the heat capacity of air, t_l is leaf temperature, t_a is air temperature, r_{ah} is the boundary layer resistance of the leaf to sensible heat transfer, and the numeral of 2 ensures that H represents the sensible heat transfer from both sides of the leaf.

Net radiation can be expressed as follows:

$$R_n = a\,R_s - R_l\ , \quad \text{......} \quad (3)$$

where R_s is the impinging shortwave radiation, a is leaf absorptance for solar radiation, and R_l is the longwave radiation budget of the leaf. With several theoretical and empirical assumptions on r_{ah}, a, and R_l[2,3,11], the following equation is obtained:

$$\mathrm{Tr} = \{ R_n - 6.67 \times 10^{-3} \rho Cp(u/L)^{0.5}(t_l - t_a) \}/2\lambda. \quad \text{......} \quad (4)$$

Another expression for leaf transpiration rate is:

$$\mathrm{Tr} = k_v(e_s{}^* - e_a)/(r_{sv} + r_{av})\ , \quad \text{......} \quad (5)$$

where $e_s{}^*$ is the saturated vapor pressure at the leaf temperature, e_a is the actual vapor pressure of the ambient air, r_{sv} is the stomatal resistance for water vapor transport, r_{av} is the boundary layer resistance for water vapor transport and k_v is the conversion factor. Therefore, Tr can be computed using eq. (4) from remotely sensed data, from which the stomatal resistance, or r_{sv}, can be obtained using the following equation:

$$r_{sv} = k_v(e_s{}^* - e_a)/\mathrm{Tr} - r_{av} = \frac{2\lambda k_v(e_s{}^* - e_a)}{aR_s - R_l - 2\rho Cp(t_l - t_a)/r_{ah}} - r_{av}. \quad \text{...} \quad (6)$$

Materials and methods

The experiment was conducted in 1988 and 1989 at Tsukuba. Stomatal resistance and transpiration rate were measured on maize (*Zea mays* L.) with a steady-state porometer (Li-Cor, Ll-1600) around the horizontal part of each leaf near the top of the canopy. Before and after the porometer measurements were taken, 10 temperature measurements were obtained from the same part of each leaf with a handheld infrared thermometer (Everest, Model-110), which has a 4° field of view, a stated accuracy of ±0.5°C, and a resolution of ±0.1°C. Air dry- and wet-bulb temperatures, solar radiation and windspeed were recorded automatically every 30 sec in the central part of the field. Measurements were taken during the period from June to September under a wide range of plant and environmental conditions.

Results and discussion

The responses of transpiration and stomatal resistance to the leaf temperature were simulated under various conditions of solar radiation, air temperature, humidity and windspeed, in order to examine the behavior of the model. Fig. 1 shows their representative responses to the leaf temperature under various intensities of solar radiation. The effects of solar radiation on them were relatively great compared with those of air humidity and other factors. Both transpiration rate and stomatal resistance were very sensitive to the changes in measured leaf temperatures in all simulations.

A number of papers that referred to the relationship between leaf temperature and transpiration or water stress suggest that the leaf-air temperature differential be a simple index for indicating the degree

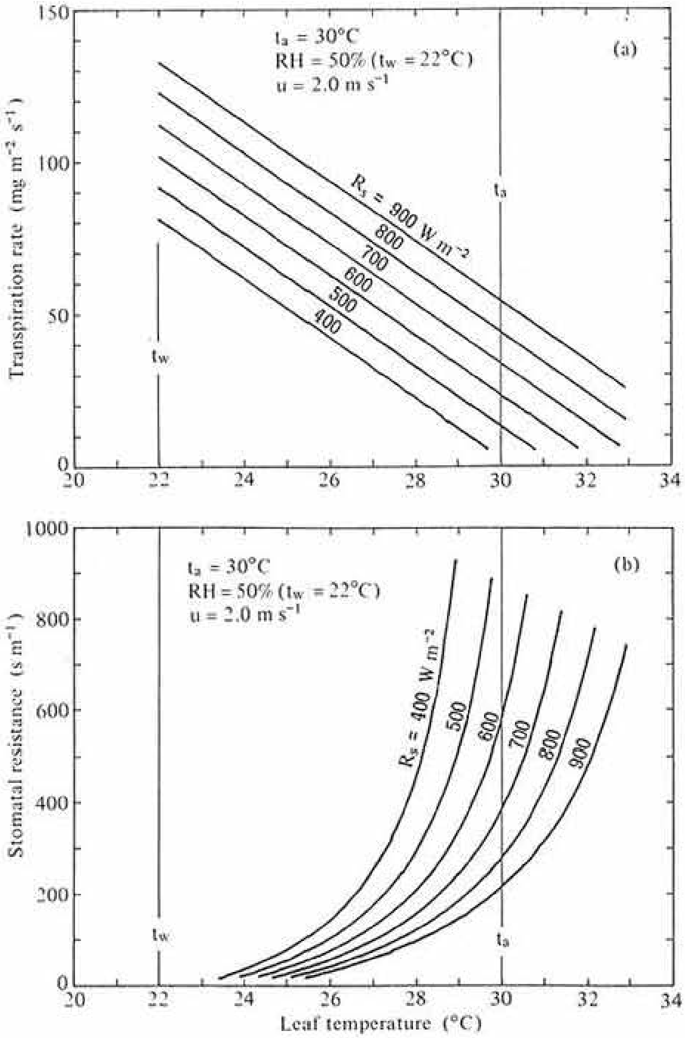

Fig. 1. Simulated responses of (a) transpiration rate and (b) stomatal resistance to the leaf temperature under various intensities of solar radiation

t_a: Dry-bulb temperature, RH: Relative humidity, u: Wind-speed, R_s: Impinging shortwave radiation, t_w: Wet-bulb temperature.

of water stress[1,4]. However, no specific relationship was found between leaf–air temperature differential and transpiration or stomatal resistance, except that higher stomatal resistance was observed more often at higher leaf–air temperature differential (Fig. 2). It is hence hard to define any specific relationship for estimating changes in transpiration and stomatal resistance.

Computed values of transpiration Tr and stomatal resistance r_{sv} by the remote method were compared with those measured by a steady-state porometer (Figs. 3 & 4). Respectable linear regression lines were obtained between calculated and measured values for both Tr and r_{sv}, the correlation coefficients of which were 0.93** for Tr and 0.96** for r_{sv}, respectively. The regression line for the r_{sv} was very close to the 1:1 line, suggesting that the "remote" r_{sv} can be a good estimate of the real r_{sv}. As for Tr, however, the regression line was far from the 1:1 line, with the porometer Tr consistently

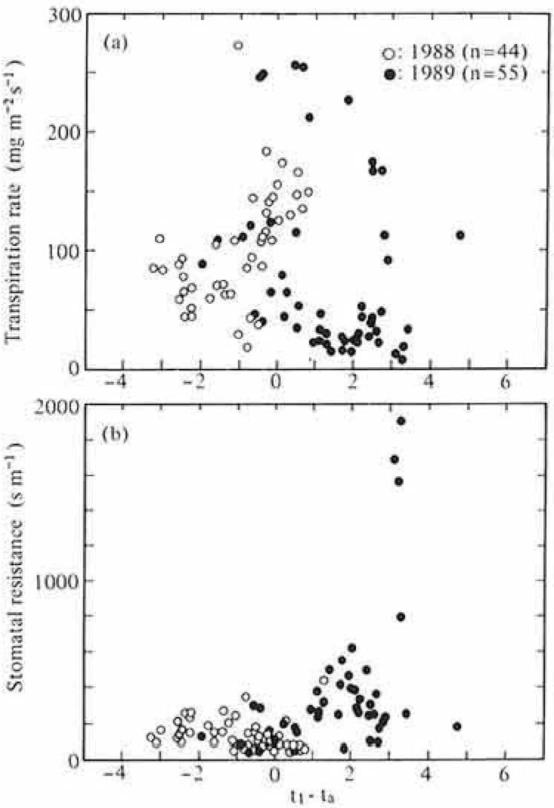

Fig. 2. Relationships of leaf and air temperature differential (t_l-t_a) with (a) transpiration rate and (b) stomatal resistance
Air temperature: 20.1–32.5°C,
Solar radiation: 178–979 W m^{-2},
Relative humidity: 50.7–75.8%,
Windspeed: 1.0–3.8 m s^{-1},
Time: 9:42–16:36.

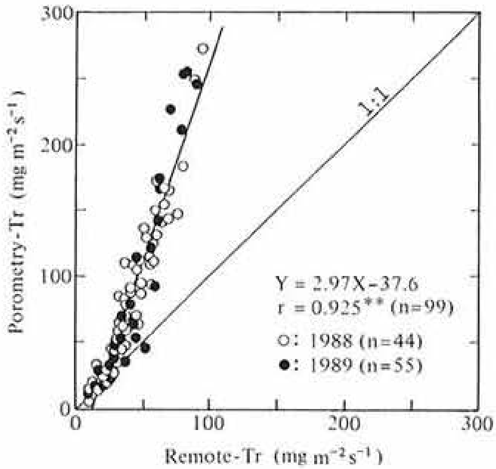

Fig. 3. A comparison between the "remote" transpiration Tr estimated by the model and the measured Tr with a steady-state porometer
Data used are the same as in Fig. 2.
** Significant at 1% level.

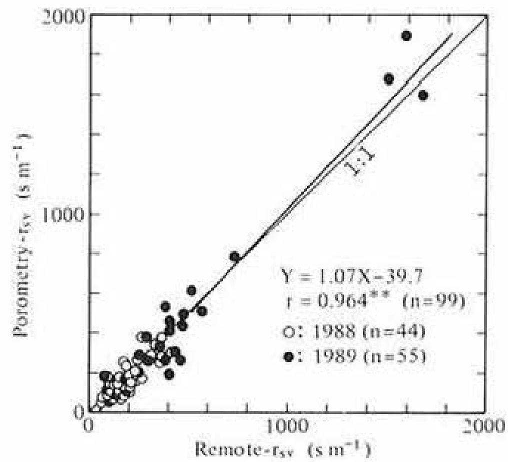

Fig. 4. A comparison between the "remote" stomatal resistance r_{sv} by the model and the measured r_{sv} with a steady-state porometer
Data used are the same as in Fig. 2.
** Significant at 1% level.

higher than the "remote" Tr. This phenomenon seems attributed to the drier air and the higher windspeed in the cuvette of the porometer. In fact, the cuvette-humidity was always lower than the ambient humidity with a correlation coefficient of 0.82**. The lower humidity and relatively great air-flow rate, i.e. greater evaporative demand and smaller boundary-layer resistance, in the cuvette resulted in higher cuvette Tr values. Nevertheless, transpiration values measured by the porometer could not behave without system, but possibly reflected the real values of Tr, because the steady-state porometer used the initial value of "open"-air humidity which was measured each time just before clumping a leaf, and also because the boundary-layer resistance within the cuvette was estimated from 15 to 45 s m^{-1} from measurements on filter papers with various wetnesses. Those resistance values were not unusually low in comparison with the calculated ones by the model. Consequently, Tr by the porometer seems competent in case of relative comparison.

The model used here could basically be applicable to various crops, because it consists of equations about biophysical processes containing few empirical or statistical parameters. The results obtained here suggest that this model combined with remotely sensed data provide fairly good estimations for diagnosis. The applicability of this model was also supported by some other experiments on wheat and soybean in Japan[10,12,15] and on cotton under the semi-arid climate in Arizona, USA[11].

Several points, however, in both direct and remote methods would have to be discussed as follows, since they might possibly be the causes of errors in estimations:

(1) Due to limitations of the porometer used, Tr and r_{sv} were obtained only for the bottom (abaxial) surface of each leaf, while calculated values were averages for both sides. Hence, values from the two methods should not necessarily fall on the 1 : 1 lines both in Tr and r_{sv}. Nevertheless, stomatal behavior is presumably similar on both sides of a leaf, so that porometer data on one side seem representative for a whole leaf.

(2) Micro-meteorological conditions in the porometer cuvette were different from those in the ambient air, which undoubtedly caused the porometer Tr's to be consistently higher than the calculated ones. Specifically, leaf temperatures measured by a fine thermocouple, as well as air humidities within the cuvette, were somewhat different from those in the ambient air. However, realistic values of stomatal resistance can likely be calculated using those data inside the cuvette, because time constants of stomatal response to changing environmental factors are generally much longer than the time needed for measurements[3], and also because parameters such as leaf temperature and air humidity are provisional measurements for calculating stomatal resistance and should not necessarily be the same as those outside the cuvette. Monteith[19] has lately proved that the observations of stomatal resistance and infrared temperture measurements by Idso et al.[5] were fully compatible based on theoretical reexamination, which involved that the "discrepancy"[5] between porometry and infrared thermometry would disappear. Hence, the stomatal resistance seems to be the most reliable parameter of the plant status under "open" conditions among all the measurements obtained with the instrument.

(3) The boundary-layer resistance was theoretically expressed in a simple form, assuming that the boundary layer was laminar, though such an assumption might be somewhat different from what occurred in nature. Also, the measured air temperature and humidity above a canopy may not exactly be the same as those just outside the boundary layer of each leaf because of their spatial gradients.

The feasibility of estimating transpiration rate and stomatal resistance with a remote method was demonstrated, although further testing and improvement in accuracy are warranted in order to take account of the several points as discussed above. This method could prove useful for agricultural water management, as well as for assessing plant responses to the environmental stress in the field. An infrared thermography system has enabled to obtain temperature data by more than 100,000 pixels in an instant[6,12,16] which can be used as inputs to the present model. On the other hand, the sensitivity of sensors mounted on a satellite, which can observe agricultural fields from the height of 800 km, is around 0.1°C. According to recent papers[8,14], furthermore, a close linear relationship was shown between photosynthesis and ratios of transpiration to vapor pressure deficit, suggesting that the photosynthetic activity can also be estimated by a remote method. Thus, the present results provide a basis for the ground-level diagnostics of crop status, but also for the long-distance or wide-area remote sensing of environmental stress.

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