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Full Paper

Detecting drought stress in longan tree using thermal imaging

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Abstract: Thailand is the world's number-one producer of longan fruit. In general, longan production takes place during the dry season under irrigation. Recently, more attention has been given to water-efficient irrigation. Water stress detection by thermal imaging, which is a non-invasive and rapid assessment method, may be an interesting tool for improved irrigation planning. In this study, four potted longan trees were subjected to water stress. Stress responses in terms of stomatal resistance (r_s) and leaf water potential (LWP) were monitored and compared with a non-stressed control. Based on thermal imaging, the crop water stress index (CWSI) was determined throughout the experiment for all trees and correlations with classical parameters were investigated. A field experiment was also carried out with 20 field-grown longan trees, either subjected to water stress treatment or serving as controls; trees were monitored for r_s, LWP and CWSI. Under controlled conditions there was a high correlation between CWSI and both r_s and LWP during the entire experimental period. In the field experiment it was found that CWSI was best correlated with r_s when images were taken from the shaded side of the leaves. A threshold value of 0.7 for CWSI is proposed to distinguish between stressed and non-stressed longan trees.

Keywords: *Dimocarpus longan*, irrigation, crop water stress index, stomatal resistance, leaf water potential, thermal imaging, drought stress, longan tree

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INTRODUCTION

Longan (*Dimocarpus longan* Lour.) is a perennial subtropical fruit tree indigenous to South-east Asia. Together with lychee (*Litchi chinensis* Sonn.), it is the most popular member of the Sapindaceae family, which has over 2,000 species and 150 genera [1]. Even though longan flowering can reliably be induced through the application of potassium chlorate and thus production is possible all year round [2], presently about 80% of longan fruit is produced during the 'on-season', which starts with flowering in February and with fruits mainly harvested in July.

Longan trees are particularly sensitive to drought during the flowering and early fruit development stages [3]. Thus, irrigation management is crucial in growing regions which have a distinctly summer rainfall pattern [4]. As on-season flowering and fruit development coincides with the dry season in Thailand, high fruit yields can only be obtained using irrigation. Irrigation water requirements are calculated using a crop coefficient (k_c) of 0.83, based on empirical data from Diczbalis [5], or 0.85 as determined by Spohrer et al. [6] based on physiological measurements of lychee trees, assuming low evaporation ($k_e = 0.05$) as achieved by micro-irrigation. Since limited water resources create an obstacle for increased longan production, deficit irrigation strategies have recently been investigated. They are summarised in the following paragraph.

Experiments in commercial orchards in Thailand have shown that partial root-zone drying (PRD) with a replenishment by irrigation of 66% of the calculated evapotranspiration (ET_c) does not cause a significant reduction in yield or fruit quality as compared to a 100%-watered control [7]. As a result, under conditions of extreme drought, deficit irrigation can help to ensure stable yields, and lower irrigation water use can reduce electricity costs for water pumping even when water is cost-free [8]. In a previous study, PRD under controlled conditions (with 60% of ET_c) was applied to three-year-old longan trees grown under a plastic shelter. The trees subjected to PRD showed stunted vegetative growth without noticeable foliar wilt. During 28 weeks of the experiment, the control trees gave two flushes while those subjected to PRD gave only one flush but with a higher number of leaves and shorter shoots than those developed in the control during the first flush [9]. Furthermore, reduced concentrations of phosphorus and potassium were found in the leaf tissues of PRD-irrigated longan trees [10]. These findings on reduced biomass formation may indicate similar long-term effects in longan as have been reported for other tree species, such as the lower crown volume found in almonds [11], and the reduced root-biomass growth shown in peach trees [12]. However, other studies of mango under similar climatic conditions to those found in Thailand, which has an intensive rainy season, have not revealed any long-term negative impact on yields [13]. In the light of this, there is a need for more research on the response of longan trees to drought stress.

Plants under water stress close their stomata to reduce transpiration. The leaf temperature thus increases as a result of a lower evaporative cooling, which can be detected by infrared thermometry. To quantify the level of water stress by infrared thermometry, several methods have been reported. Idso et al. [14] proposed that the accumulated difference between air temperature (T_a) and canopy temperature (T_c) be considered for calculating stress degree days. This, however, does not take into account the vapour pressure deficit (VPD), net radiation or wind speed. Therefore, the 'crop water stress index' (CWSI) was introduced. The CWSI correlates canopy temperature to the upper (dry) and lower (wet) reference temperatures. It is inversely correlated with leaf water potential (LWP) [15]. Alternatively, the 'I_G-index' [16] can be calculated based on the same references. It is proportional to the stomatal conductance.

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The introduction of thermal imaging has added new possibilities to stress detection by IR thermometry. Generally, the advantage of thermography is that a semi-automatic stress analysis of large areas of a canopy can be achieved with much more effective replication than when using porometry, thus providing great benefits for comparative studies such as screening activities [17]. As a consequence, the effective use of thermography for breeding purposes has been demonstrated under laboratory conditions for the identification of mutants [18], as well as for the phenotyping of rice under field conditions [19]. Results of greenhouse experiments with different ornamentals suggest that there is a potential use of thermal imaging for scheduling the deficit irrigation of hardy nursery stock [20].

Another promising application of thermal imaging in agriculture is in the development of precision irrigation as this process facilitates the mapping of water status variability [21]. As a result, variability maps can be developed from ground-based thermal imaging using, for example, cameras mounted on irrigation machines, which can then be correlated with aerial images [22, 23]. Due to the high costs and logistical requirements involved, the use of this technology has so far been restricted to industrialised countries. The practical application of thermal imaging in the field depends on obtaining reference data, which is crop-specific. Most studies on the application of thermal imaging so far have been carried out on grapevine [24, 25]. Further information is available on its use for annual crops such as wheat [26, 27], rice [19], maize [28] and cotton [22]. As for fruit trees, apple, peach [29] and olive [23, 30] have already been investigated using thermal imaging.

Longan, as a drought-sensitive plant, is expected to show a pronounced increase in leaf temperature as a result of stomatal closure, which could be reliably detected. The aim of this study is to ascertain the CWSI threshold appropriate for determining the presence of water stress, as well as the time of day and the level of image exposure most suitable for drought stress monitoring for longan trees.

MATERIALS AND METHODS

Plant Material and Irrigation Treatment

Pot experiment

One part of the experiment was carried out using potted longan trees kept under a transparent plastic shelter at Maejo University in San Sai district, Chiang Mai province, Thailand (18° 53’ N 99° 00’ E, 320 m above m.s.l.), from the 12^{th}-18^{th} of February 2009 during the dry season with a clear sky during the entire period of observation. Eight longan trees had been cultivated in sand culture for three years prior to the experiment. For the study, pots with a diameter of 35 cm were drained and the trees irrigated daily until drainage water was visible. A modified Hoagland solution [31] was applied as liquid fertiliser once a week. At the start of the experiment, the trees were subdivided into two groups: S_{dry} and S_{irri}. Irrigation was completely stopped for S_{dry} while S_{irri} served as a control and were continuously irrigated as prior to the experiment. No fertiliser was applied during the experimental period. The pots were positioned in one row in an east-west direction, alternating between treatment and control. To the south of the pots, a 3-m space enabled the taking of digital and thermal images, while to the north a black plastic sheet was hung at a distance of 50 cm behind the trees to serve as contrast.

Field experiment

The field experiments were carried out at Maejo University experimental station (18° 55' N, 99° 02' E, 380 m above m.s.l.), where the soil is a loamy sand and has an average content of 67.8% sand, 25.8% silt and 6.4% clay. The soil can be classified as orthic acrisol, which is derived from sandstone and phyllite and has an approximate depth of 50 cm. The stone content is high (>35%), and the field capacity ranges between 10.89-12.78%. The permanent wilting point is between 5.77-6.45%. Five-year-old longan trees were planted in a 6×6 m pattern. The canopies had an average diameter of 3 m. Prior to the experiment, all the trees were irrigated in order to obtain a uniform soil water potential (SWP) of −200 mbar. The experiment started on March 5, 2010 during the dry season with a clear sky and was stopped on March 19 as some clouds appeared followed by rain. During the period of the experiment the longan trees flowered. In total, 20 trees divided into two groups were arranged in four rows, alternating between the treated and control trees within each row. Irrigation was completely stopped for 10 trees in the F_{dry} group while 10 trees in the control group (F_{irri}) were irrigated once per week with 22 mm of water.

Monitoring of Soil Water Content and Drought Stress Responses

Volumetric water content was determined by time-domain reflectometry using a Tektronix 1502B cable tester (Tektronix, USA) and a self-built probe everyday for each pot and every three days at three depths for one tree per treatment in the field experiment. The SWP was determined through the use of a tensiometer set (Rain Drop, Thailand) at 30-cm soil depth for each treatment. Pre-dawn LWP was determined by use of a Scholander-type pressure chamber (PMS Instrument, USA). Measurements took place everyday for the pot experiment on three randomly picked leaves from each tree, and every third day for the field experiment on ten leaves per treatment. Each time a thermal image was taken, the respective stomatal resistance (r_s) to water vapour of three randomly selected leaves was determined within 10 min. using an SC-1 diffusion porometer (Decagon Devices, USA). For all the experiments, temperature (T), relative humidity (RH), wind speed (u) and air pressure (p) were monitored by a portable weather station (PCE-FWS 20, PCE Group, Germany), which was installed at the experimental site. In addition, the solar radiation data were made available from an IrriWise™ irrigation control unit (Netafim, Israel) set at a 500-m distance from the experimental plots. The VPD was calculated as the difference between the saturated vapour pressure at temperature T ($e^0(T)$) and the actual vapour pressure (e_a), where $e^0(T) = 0.6108 \ln(17.27T/T+237.3)$ and $e_a = e^0(T)*(RH/100)$ [32].

Thermal Images

Image acquisition

For the pot experiment, thermal images of each tree were taken at noon by a thermo-camera (VarioCAM, InfraTec, Germany) and two adjacent trees were captured per image. One leaf on each tree was covered with petroleum jelly to serve as a dry reference. The ceramic head of a tensiometer was filled with water to serve as wet reference. This artificial reference surface (ARS), set up as described by Zia et al. [25], was hung between each pair of trees. For the field experiment, images were taken everyday at 2 p.m. using a thermo-camera (InfraCAM SD, FLIR Systems Inc., Sweden) set at a distance of 5 m from both the sunlit side and the shaded side. Once per week, images were taken every hour throughout the day. One leaf from each tree was sprayed with water 10 sec. prior

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to thermal image acquisition to serve as a wet reference, and another leaf was covered with petroleum jelly to serve as a dry reference. After every thermal image, a digital photo of the same set-up was taken with a digital camera (Cybershot, Canon, Japan).

Data processing

The images obtained for the pot experiment were evaluated using IRBIS 2.2 software. A polygon was fitted around the canopy of the respective trees and the canopy temperature (T_c) determined as an average value for the polygon. In addition, a rectangle was placed around both the ARS and the coated leaf in such a way that the minimum and maximum temperatures within the rectangle represented the wet (T_w) and dry (T_d) reference temperatures respectively. Images taken from the field experiment were evaluated using ThermaCAM Researcher Professional version 2.1 software. Photographs taken of the sunlit and shaded sides were analysed separately by fitting a polygon around the canopy in order to determine T_c. A rectangle was fitted around the sprayed and the coated leaves; T_w and T_d were represented by the minimum and maximum temperatures of the rectangle respectively. For both the sunlit sides and the shaded sides, the CWSI was determined according to Idso et al. [14] as: CWSI = $(T_c - T_w)/(T_d - T_w)$. Higher values of CWSI represent higher stress. The theoretical maximum of CWSI is 1.0 if $T_c = T_d$, which indicates complete stomatal closure. Differences between treatments were analysed for significance by one-way ANOVA using Origin 5.1 computer code (Microcal Software, USA). The significance of correlation between two factors was tested using SPSS software version 11.5 (SPSS, USA).

RESULTS

Pot Experiment

After stopping irrigation for the S_{dry} group, the substrate (growing medium) moisture content decreased quickly within the first four days (Figure 1A) and this resulted in a subsequent significant decrease in LWP. Beginning on the fifth day of the experiment, water stress became severe and the LWP doubled in plants under non-irrigated treatment (Figure 1B). From the fourth day onward, stomatal resistance significantly increased as compared to the control (Figure 1C). From the second day, the CWSI value was lower in the S_{irri} than the S_{dry} treatment, but this difference became statistically significant only when drought stress was severe (Figure 1D). Throughout the experiment the CWSI averaged below 0.8 for S_{irri} and above 0.8 for S_{dry}. A positive correlation was found between CWSI and stomatal resistance with a coefficient of determination (R^2) of 0.55, while a high negative correlation was found between CWSI and pre-dawn leaf water potential (R^2 = 0.62). Furthermore, a high correlation found between CWSI and substrate moisture (R^2 = 0.55) indicates that drought stress was the driving factor that increased CWSI in the trees subjected to stress treatment (Figure 2).

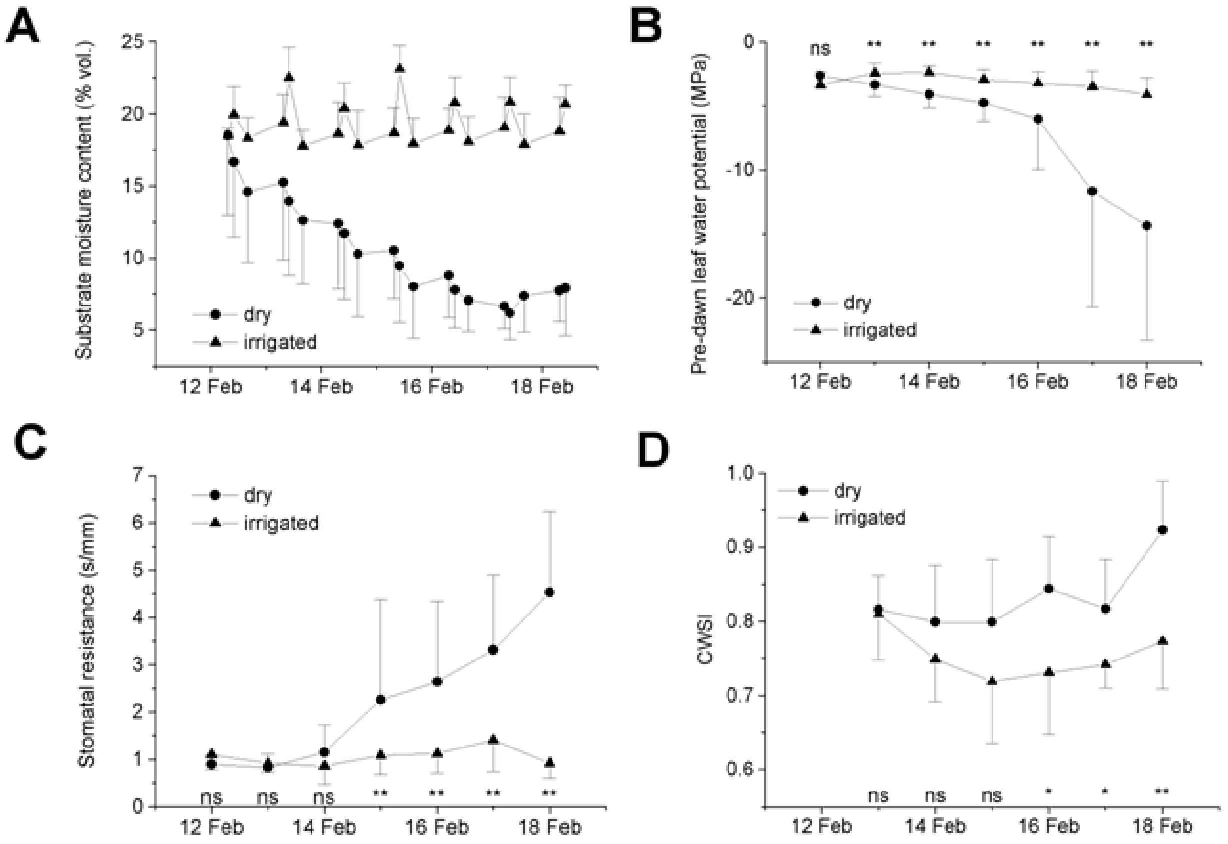

Figure 1. **A:** Volumetric moisture content of the substrate in pots containing irrigated and non-irrigated longan trees. **B:** Pre-dawn leaf water potential of irrigated and non-irrigated potted longan trees. Data points are the average of 12 leaves. **C:** Stomatal resistance of irrigated and non-irrigated potted longan trees. Data points are the average of 20 leaves. **D:** Crop water stress index (CWSI) for irrigated and non-irrigated potted longan trees. Data points are the average of four trees. Error bars represent ± SD. Data points marked with * and ** differ significantly from the control at $\alpha = 0.05$ and 0.01 resprectively. Non-significant differences are marked with 'ns'.

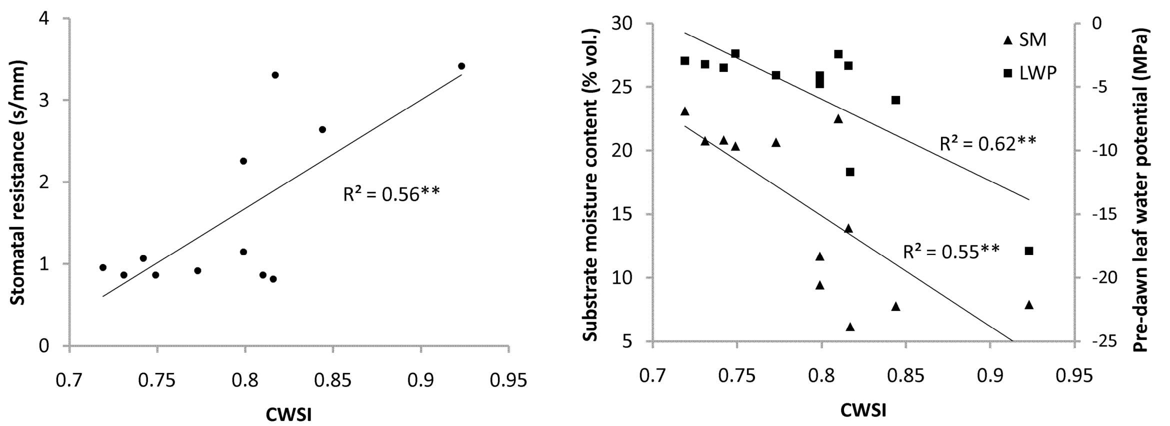

Figure 2. Correlation between crop water stress index (CWSI) and stomatal resistance (left) and between CWSI and pre-dawn leaf water potential (LWP) and substrate moisture (SM) (right) in potted longan trees. Correlations marked with ** are significant at $\alpha = 0.01$.

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Field Experiment

The overall amount of water available in the soil was very low due to a high stone content, but the trend for the irrigated trees (F_{irri}) was clearly different from that of the non-irrigated trees (F_{dry}). Three days after the start of the experiment, the soil in the F_{dry} treatment had dried out, and at the end of each period between one irrigation and the other, a decreased SWP was observed in the control group, although the values were in a range where no water stress would be expected. Meanwhile, the soil in F_{dry} group dried out quickly, reaching SWP values below −800 mbar; tensiometer readings were obtained by refilling the tensiometer daily. This method underestimates the real SWP. Therefore, SWP values are estimated based on water retention curve and volumetric soil moisture values obtained by the time-domain reflectometry readings (Figure 3).

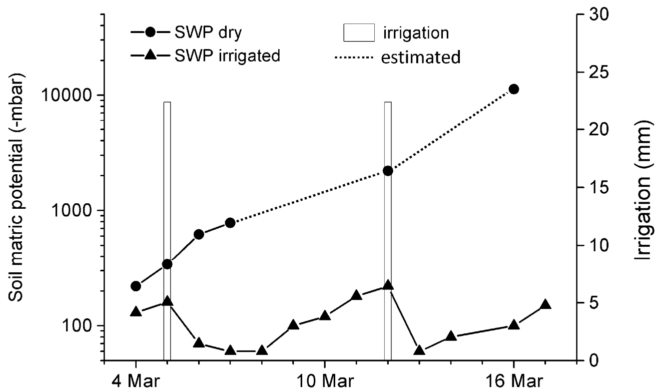

Figure 3. Soil water potential (SWP) and irrigation water application during the field experiment. The dotted line represents estimated values for SWP_{dry} below the measurement range of the tensiometer, based on soil moisture determination.

LWP measurements show stress responses of the non-irrigated trees; after only a few days of the experiment, differences between the treated and control trees become apparent (Figure 4A). A strong correlation between SWP and pre-dawn LWP (data not shown) is inherent in the nature of the measurement as before the start of transpiration there is an equilibrium between both potentials. The monitoring of r_s indicates increased resistance values in the F_{dry} treatment immediately after the start of the experiment with significant differences appearing after one week compared with control trees (Figure 4B).

An analysis shows differences in CWSI between the shaded and sunlit sides of the canopy. Due to a higher temperature on the reference surface, CWSI on the sunlit side was lower than on the shaded side even though the absolute canopy temperature was high because of the influence of radiation. One week after the start of the experiment, the average canopy temperature on the sunlit side of the F_{dry} group was higher than that of the control group, although differences in CWSI were not significant (Figure 4C). At the same time, based on thermal images of the shaded side, the CWSI was significantly higher in F_{dry} treatment as compared to control. While CWSI of the control averaged below 0.7, that of the trees under stress treatment was above 0.7 on average (Figure 4D). A low positive correlation between CWSI and r_s is found on the shaded side (R^2 = 0.34) while there is no correlation between the CWSI and r_s on the sunlit side (R^2 = 0.09) (Figure 5). By analogy, CWSI and SWP are correlated (R^2 = 0.39) on the shaded side, but not on the sunlit side (R^2 = 0.29) (Figure 6)

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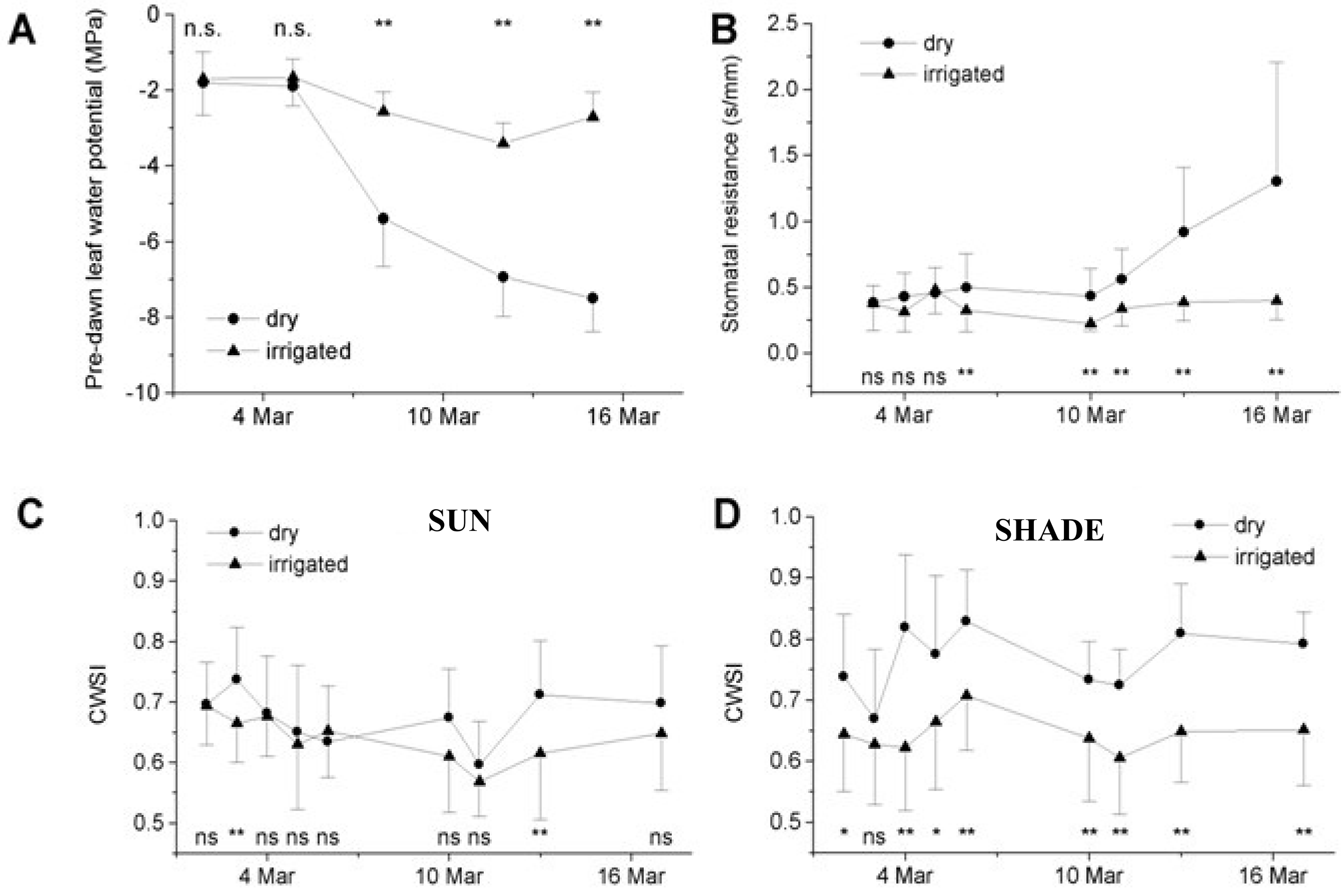

Figure 4. A: Pre-dawn leaf water potential (LWP) of irrigated and non-irrigated field-grown longan trees. Data points are the average of 10 leaves. **B:** Stomatal resistance of irrigated and non-irrigated field-grown longan trees. Data points are the average of 20 leaves. **C, D:** CWSI determined from sunlit and shaded sides of the canopy respectively. Data points are the average of 10 trees. Error bars represent ± SD. Data points marked with * and ** differ significantly from the control at α = 0.05 and α = 0.01 respectively. Non-significant differences are marked with 'ns'.

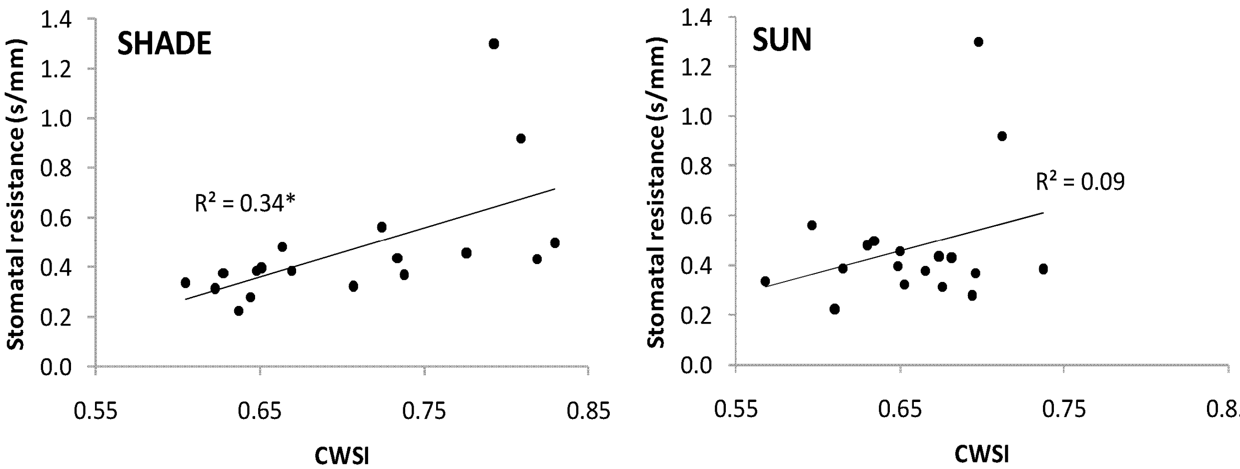

Figure 5. Correlation between stomatal resistance and CWSI in the shade (left) and on the sunlit side of the canopy (right). Correlation marked with * is significant at α = 0.05.

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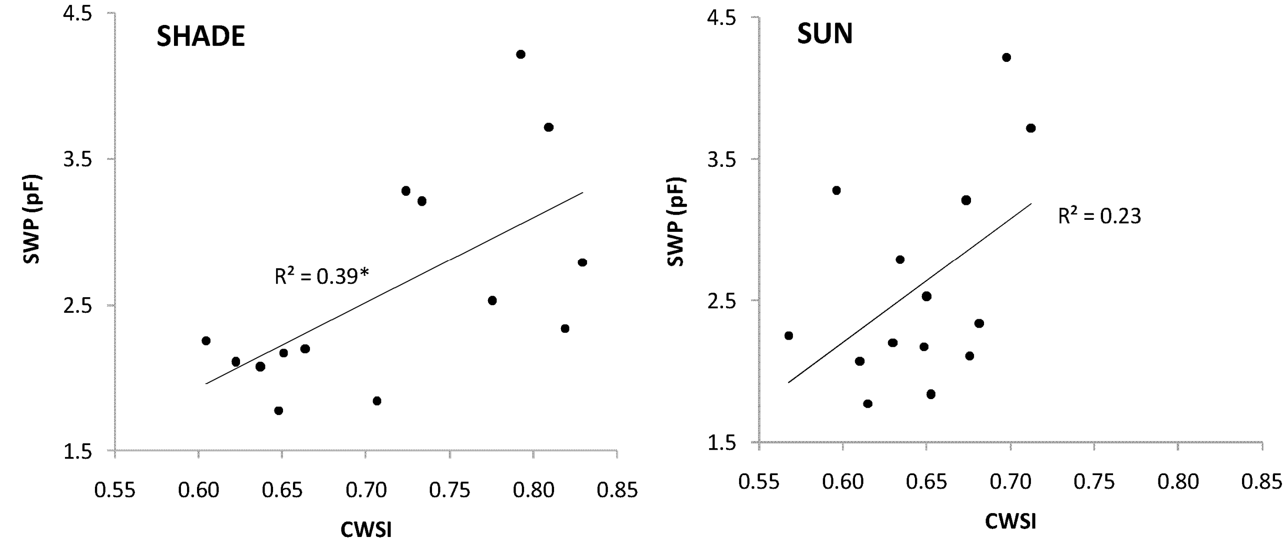

Figure 6. Correlation between soil water potential (SWP) and CWSI in the shade (left) and on the sunlit side of the canopy (right). Correlation marked with * is significant at $\alpha = 0.05$.

Figures 7A and 7B show the development of stomatal resistance during the course of a day. A typical pattern of rather low resistance in the morning together with a low VPD followed by a peak in the afternoon was observed for trees undergoing stress treatment. The stomatal resistance of control trees was lower in general and with a less pronounced increase during the day.

Differences in stomatal aperture during the morning hours were small and minor differences were observed in the CWSI before noon. However, between noon and 3 p.m., differences in CWSI were at their highest. In the shaded part of the canopy, differences between the stressed and non-stressed trees were more pronounced than in the sunlit area. Between 4 p.m. and sunset, differences in CWSI decreased as the effect of evaporative cooling in the non-stressed leaves decreased and canopy temperature converged to the dry reference temperature in both treatments (Figures 7 C-F).

DISCUSSION

The soil water potential (SWP) is the most important variable for estimating the plant water status under prevailing conditions. It is commonly measured in millibars (mbar) or pF (log mbar) and indicates how strongly the water is bound to the soil. If SWP is at approximately -100 mbar (pF 2.0), the soil has reached field capacity and the plants are well supplied with water. The start of water stress is crop dependent; while stress in vegetables may start at SWP = -400 mbar (pF 2.6), most trees do not suffer from water stress above -700 mbar (pF 2.8). When the permanent wilting point is reached at approximately -15,000 mbar (pF 4.2), no plant growth is possible. The leaf water potential (LWP) indicates how strongly water is bound to the plant tissue. Before the start of photosynthesis SWP and LWP should be in equilibrium; that is why the pre-dawn LWP is a good indicator of plant stress. With the start of photosynthesis in the morning hours, stomata open and the size of the stomatal aperture is regulated by the plant. With a reduced stomatal aperture the conductance decreases and the stomatal resistance to water vapour (r_s) increases. As a consequence, gas exchange is reduced. The determination of r_s as inverse value of stomatal conductance is an indicator of plant stress. The amount of transpiration is further influenced by the vapour pressure deficit (VPD), which is a measure of the evaporative demand of the air under prevailing air temperature and relative humidity.

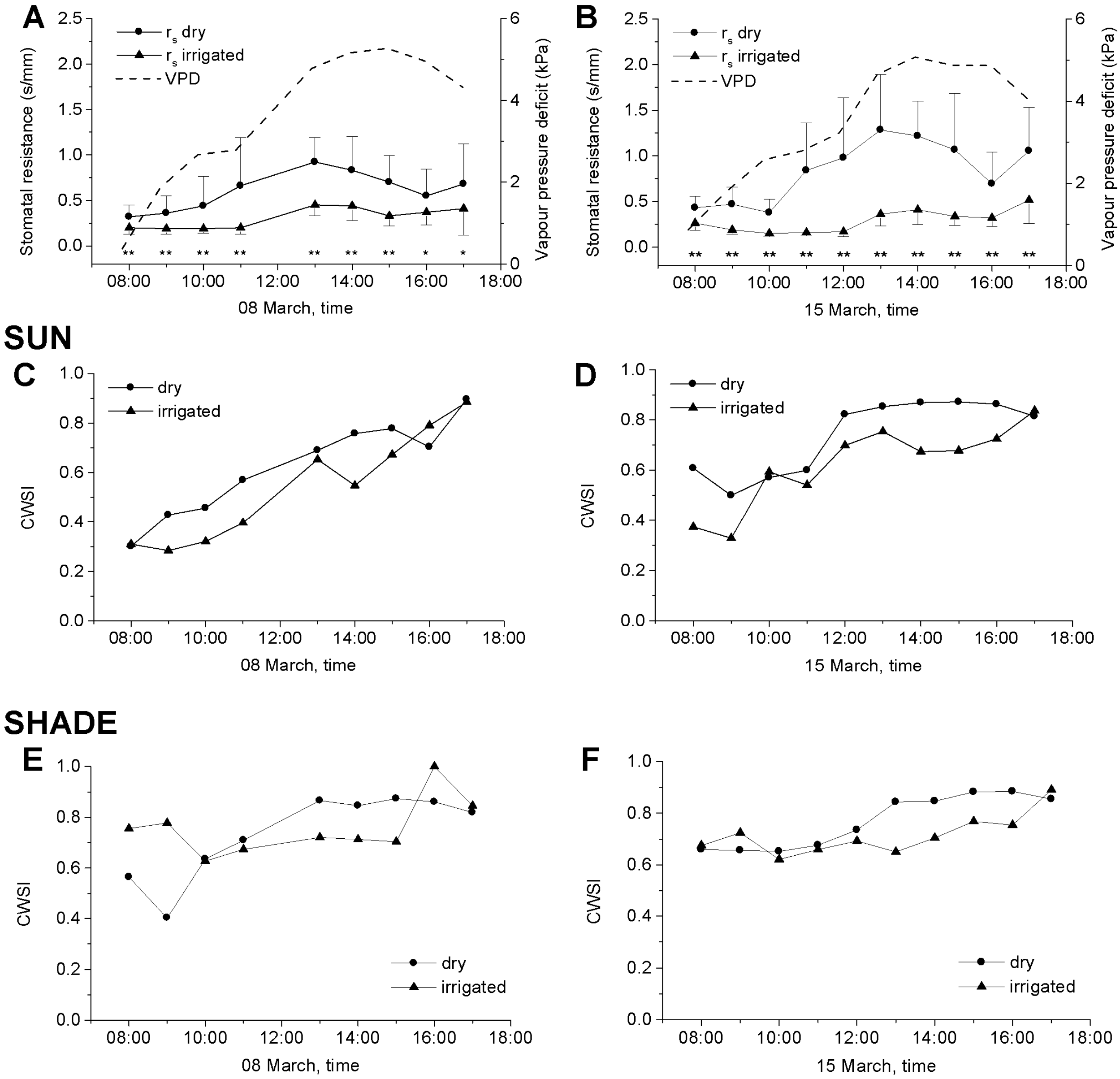

Figure 7. A, B: Vapour pressure deficit (VPD) and stomatal resistance of irrigated and non-irrigated field-grown longan trees 7 days (left) and 14 days (right) after the start of treatment. **C, D:** CWSI in the sun after 7 and 14 days. **E, F:** CWSI in the shade after 7 and 14 days. Data points of stomatal resistance are the average of 5 leaves; error bars represent ± SD. Data points marked with * and ** differ significantly from the control at α = 0.05 and α = 0.01 respectively. Data points of CWSI represent one analysed picture.

In this study the determination of pre-dawn LWP is shown to be the most reliable method for early detection of water stress since under controlled conditions both in pots and in the field, the LWP decreases quickly as drought is imposed on the longan trees. There is a good correlation between pre-dawn LWP and CWSI under controlled condition, similar to an earlier report in which the CWSI was correlated with the midday LWP [21]. Pre-dawn LWP is closely correlated with SWP, so the differences between well-watered and drought-stressed plants can be visible at a very early stage. Similar to soil moisture, LWP is an indirect stress variable, one which is not necessarily expressed through the plant's reaction such as stomatal closure or decrease in photosynthesis. From the values of r_s, stomatal closure seems to start later and show a greater variation, which indicates that plants, especially field-grown longan trees which differ considerably in size and root development, react differently to the same environmental conditions.

The r_s produces reliable data on plant water stress reactions, and the increase in r_s observed after two weeks under field conditions suggests that once-per-week irrigation is adequate to avoid plant drought stress, although a longer interval may be applied if water availability or water conveyance infrastructure is limited. Direct application of r_s monitoring for irrigation is, however, hampered by spatial and temporal variability in the field as it requires a large number of observations within a narrow time slot. As in previous studies [16, 17, 33], thermal imaging is successfully correlated with r_s (Figures 5 and 7**)**.

Even though the correlation coefficients (R^2) found in this study are lower than those previously reported by Jones [16], the overall trend shows CWSI to be a reliable water-stress indicator. Under controlled conditions as in the field, there is a higher correlation between CWSI and the classic stress parameters. Small trees generally show less variability in terms of stomatal closure. Pot experiments offer a better view with fewer discontinuities in the determination of the average temperature by thermal imaging, while in the field apart from weather conditions, the canopy architecture, namely leaf angle, can influence the measurements. This is also an observation which has been reported earlier [24]. It has been found that a combined thermal and visible imaging can improve the accuracy of remote drought stress detection [25, 34]. Where this is not possible, for example when using a simple thermal camera without simultaneous digital image acquisition, it has been shown that averaging temperatures over several leaves per canopy, as performed in this study, can compensate for differences in leaf angle [24].

However, if the canopy temperature is determined as mere average, thermal images must be taken on the shaded side of the canopy. If images are taken on the sunlit side, it is not possible to establish a meaningful correlation between CWSI and r_s. This observation is supported by Fuchs [35], who found greater differences in leaf temperature between stressed and unstressed plants in the shade than on the sunlit part of the canopy; and by Jones et al. [17], who suggested that CWSI is less varied in a shaded canopy compared with a sunlit one. With advanced image analysis, it is possible to discriminate between the shaded and sunlit parts of a row crop such as vine [36]. However, the influence of radiation on a heterogeneous canopy of the longan tree is greater than on the canopy of a row of grapevines. Apart from the increased complexity of the apparent temperature composition due to canopy architecture, there is also a greater variability of stomatal aperture under the influence of direct radiation. Thus, the monitoring of the sunlit side of the canopy is not directly applicable to longan trees.

The choice of reference surface influences the order of magnitude of the CWSI, and so if values are to be communicated, the kind of reference surface used has to be taken into account. In this study, as in most previous studies, petroleum-jelly-coated leaves were used throughout the measurements. This method is convenient as coated leaves remain on the plant and do not require preparation for each measurement, and since they are in continuous thermal exchange with the

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surrounding environment, they give a reliable value of the temperature of non-transpiring leaves. Water-sprayed leaves, as a lower reference, involve a more time-consuming process as water has to be sprayed prior to acquisition of each thermal image. This method also requires that an exact timing and precise working procedure be used. The time between the spraying of the wet reference leaf and the taking of the image must be standardised; all plants and references must be subjected to a similar radiation environment and the imager must be allowed to equilibrate before each measurement [37]. Thus, in this study the porous cup of a tensiometer was additionally used as an artificial reference surface (ARS) in order to represent the lower reference temperature. Porous tensiometer cups were used as ARS in an earlier study [25] while ARS in another study consisted of a textile material soaked in water [22]. It may also be possible to use an evaposensor for both the wet and dry references as introduced in an earlier study on irrigation scheduling [38].

In the present study, by using both types of references, water stress monitoring is possible. Based on the results, we consider the CWSI of 0.7 as an appropriate threshold for detecting the occurrence of water stress when using a sprayed leaf as wet reference. This value would be higher if an ARS had been used. Since an ARS had not been applied in the field, a threshold value of 0.7 for CWSI should be communicated for field-grown longan trees.

In general, under the influence of a high VPD (high air temperature and low relative humidity), the stomata close to prevent the tree from experiencing excessive water loss. From CWSI measurements taken during the course of day, it can be inferred that the best time to determine the CWSI is between noon and early afternoon. Coinciding with the highest level of VPD, stressed longan trees have already closed a greater part of their stomata at this time while unstressed trees still show high levels of stomatal conductance. During the daily maximum of radiation and air temperature, stressed leaves heat up to a greater extent than unstressed leaves, but from about 4 p.m. onwards, even the unstressed leaves start to close their stomata, and as a result the CWSI no longer differs between stressed and unstressed leaves.

CONCLUSIONS

Thermal imaging can be used for drought stress detection in longan trees based on image processing and by averaging a randomly selected part of the canopy. Differences between stressed and unstressed longan trees can be detected before the appearance of visible signs such as changes in leaf angle and leaf rolling. In contrast to other stress-monitoring methods, no destructive or invasive measurements are undertaken, which paves the way to remote sensing, although this technique has not yet been considered as a part of this study. It was found that measurements necessary to calculate CWSI should ideally be taken during the early afternoon in the absence of wind and clouds, and preferably on the shaded side of the tree. Under these conditions, it is possible to distinguish between drought-stressed and well-watered trees on the same plot. However, for a reliable stress determination, temperature measurements by thermal imaging should be conducted over several days as the CWSI may change due to heterogeneous climatic conditions. This problem was also encountered when determining stomatal conductance. The use of thermal imaging for stress detection in practice requires robust references—those which can be correlated with the occurrence or even the intensity of stress. Based on a proposed CWSI threshold value of 0.7 for field-grown longan trees, thermal imaging can be used for irrigation scheduling, although more research is needed on the level of irrigation intensity to be used before a practical application is possible.

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REFERENCES

1. C. M. Menzel and D. R. Simpson, "Lychee cultivars around the world", in "Australian Lychee Yearbook" (Ed. M. B. Smith), Australian Lychee Growers Association, Queensland, Australia, **1991**, pp.30-34.
2. P. Manochai, P. Sruamsiri, W. Wiriya-alongkorn, D. Naphrom, M. Hegele and F. Bangerth, "Year around off season flower induction in longan (*Dimocarpus longan*, Lour.) trees by $KClO_3$ applications: Potentials and problems", *Sci. Hortic.*, **2005**, *104*, 379-390.
3. C. Menzel and G. K. Waite, "Litchi and Longan: Botany, Production and Uses", CABI Publishing, Wallingford (UK), **2005**.
4. Y. Diczbalis, B. Nicholls, I. Groves and K. Lake, "Sapindaceae production and research in Australia", *Acta Hortic.*, **2010**, *863*, 49-58.
5. Y. Diczbalis, "Longan: Improving Yield and Quality", Rural Industries Research and Development Corporation (Australia), Barton ACT, **2002**, p.22.
6. K. Spohrer, C. Jantschke, L. Herrmann, M. Engelhardt, S. Pinmanee and K. Stahr, "Lychee tree parameters for water balance modeling", *Plant Soil*, **2006**, *284*, 59-72.
7. S. Ongprasert, W. Spreer, W. Wiriya-Alongkorn, S. Ussahatanonta and K. Köller, "Alternative techniques for water-saving irrigation and optimised fertigation in fruit production in Northern Thailand", in "Sustainable Land Use in Mountainous Regions of Southeast Asia: Meeting the Challenges of Ecological, Socio-Economic and Cultural Diversity" (Ed. F. J. Heidhues, L. Herrmann, A. Neef, S. Niedhart, J. Pape, P. Sruamsiri, D. C. Thu and A. Vallé Zarate), Springer, Berlin, **2007**, pp.120-133.
8. K. Satienperakul, W. Spreer, W. Wiriya-Alongkorn, S. Ongprasert and J. Müller, "Economic assessment of water saving irrigation methods in longan production in Northern Thailand", Proceedings of Tropentag, Conference on International Research for Development, **2006**, Bonn, Germany, pp.1-8.
9. S. Ongprasert and W. Wiriya-Alongkorn, "Yield and vegetative growth of longan subjected to partial root-zone drying irrigation", *J. Agric. Res. Extension*, **2009**, *26*, 8-17.
10. U. Srikasetsarakul, W. Spreer, S. Ongprasert, W. Wiriya-Alongkorn, K. Sringarm, P. Sruamsiri and J. Müller, "Biomass formation and nutrient partitioning in potted longan trees under partial rootzone drying", *Acta Hortic.*, **2011**, *889*, 587-592.
11. G. Egea, P. A. Nortes, M. M. González-Real, A. Baille and R. Domingo, "Agronomic response and water productivity of almond trees under contrasted deficit irrigation regimes", *Agric. Water Manage.*, **2010**, *97*, 171-181.

12. J. M. Abrisqueta, O. Mounzer, S. Alvarez, W. Conejero, Y. Garcia-Orellana, L. M. Tapia, J. Vera, I. Abrisqueta and M. C. Ruiz-Sánchez, "Root dynamics of peach trees submitted to partial rootzone drying and continuous deficit irrigation", *Agric. Water Manage.*, **2008**, *95*, 959-967.
13. W. Spreer, S. Ongprasert, M. Hegele, J. N. Wünsche and J. Müller, "Yield and fruit development in mango (*Mangifera indica* L. cv. Chok Anan) under different irrigation regimes", *Agric. Water Manage.*, **2009**, *96*, 574-584.
14. S. B. Idso, R. D. Jackson, P. J. Pinter, R. J. Reginato and J. L. Hatfield, "Normalizing the stress-degree-day parameter for environmental variability", *Agric. Meteorol.*, **1981**, *24*, 45-55.
15. G. Yuan, Y. Luo, X. Sun and D. Tang, "Evaluation of a crop water stress index for detecting water stress in winter wheat in the North China Plain", *Agric. Water Manage.*, **2004**, *64*, 29-40.
16. H. G. Jones, "Use of infrared thermometry for estimation of stomatal conductance as a possible aid to irrigation scheduling", *Agric. Forest Meteorol.*, **1999**, *95*, 139-149.
17. H. G. Jones, M. Stoll, T. Santos, C. de Sousa, M. M. Chaves and O. M. Grant, "Use of infrared thermography for monitoring stomatal closure in the field: Application to grapevine" *J. Exp. Bot.*, **2002**, *53*, 2249-2260.
18. S. Merlot, A. C. Mustilli, B. Genty, H. North, V. Lefebvre, B. Sotta, A. Vavasseur and J. Giraudat, "Use of infrared thermal imaging to isolate Arabidopsis mutants defective in stomatal regulation", *Plant J.*, **2002**, *30*, 601-609.
19. H. G. Jones, R. Serraj, B. R. Loveys, L. Xiong, A. Wheaton and A. H. Price, "Thermal infrared imaging of crop canopies for the remote diagnosis and quantification of plant responses to water stress in the field", *Func. Plant Biol.*, **2009**, *36*, 978-989.
20. O. M. Grant, M. J. Davies, H. Longbottom, R. Harrison-Murray and A. Herrero, "Application of deficit irrigation to controlling growth of hardy nursery stock", *Acta Hortic.*, **2011**, *889*, 409-416.
21. Y. Cohen, V. Alchanatis, M. Meron, Y. Saraga and J. Tsipris, "Estimation of leaf water potential by thermal imagery and spatial analysis", *J. Exp. Bot.*, **2005**, *56*, 1843-1852.
22. V. Alchanatis, Y. Cohen, S. Cohen, M. Moller, M. Sprinstin, M. Meron, J. Tsipris, Y. Saraga and E. Sela, "Evaluation of different approaches for estimating and mapping crop water status in cotton with themal imaging", *Precis. Agric.*, **2010**, *11*, 27-41.
23. J. A. J. Berni, P. J. Zarco-Tejada, G. Supulcre-Cantó, E. Fereres and F. Villalobos, "Mapping canopy conductance and CWSI in olive orchards using high resolution thermal remote sensing imagery", *Remote Sens. Environ.*, **2009**, *113*, 2380-2388.
24. O. M. Grant, L. Tronina, H. G. Jones and M. M. Chaves, "Exploring thermal imaging variables for the detection of stress responses in grapevine under different irrigation regimes", *J. Exp. Bot.*, **2007**, *58*, 815-825.
25. S. Zia, K. Spohrer, N. Merkt, D. Wenyong, H. Xiongkui and J. Müller, "Non-invasive water status detection in grapevine (*Vitis vinifera* L.) by thermography", *Int. J. Agric. Biol. Eng.*, **2009**, *2*, 46-54.
26. N. K. Gontia and K. N. Tiwari, "Development of crop water stress index of wheat crop for scheduling irrigation using infrared thermometry", *Agric. Water Manage.*, **2008**, *95*, 1144-1152.
27. S. Zia, D. Wenyong, W. Spreer, K. Spohrer, H. Xiongkui and J. Müller, "Assessing crop water stress of winter wheat by thermography under different irrigation regimes in North China Plain", *Int. J. Agric. Biol. Eng.*, **2012**, *5*, 24-34.

28. G. Romano, S. Zia, W. Spreer, C. Sanchez, J. Cairns, J. L. Araus and J. Müller, "Use of thermography for high throughput phenotyping of tropical maize adaptation in water stress", *Comput. Electron. Agric.*, **2011**, *79*, 67-74.
29. R. Giuliani, E. Magnanini and J. A. Flore, "Potential use of infrared thermometry for the detection of water deficit in apple and peach orchards", *Acta Hortic.*, **2001**, *557*, 399-405.
30. G. Sepulcre-Cantó, P. J. Zarco-Tejada, J. C. Jiménez-Munoz, J. A. Sobrino, E. de Miguel and F. J. Villalobos, "Detection of water stress in an olive orchard with thermal remote sensing imagery", *Agric. Forest Meteorol.*, **2006**, *136*, 31-44.
31. D. R. Hoagland and D. I. Arnon, "The Water-Culture Method for Growing Plants without Soil", University of California Agricultural Experiment Station, Berkeley (CA), **1950**.
32. D. Raes, "The ET_0 Calculator, Reference Manual Version 3.1", Food and Agricultural Organization of the United Nations (FAO), Rome, **2009**.
33. I. Leinonen, O. M. Grant, C. P. P. Tagliavia, M. M. Chaves and H. G. Jones, "Estimating stomatal conductance with thermal imagery", *Plant Cell Environ.*, **2006**, *29*, 1508-1518.
34. M. Möller, V. Alchanatis, Y. Cohen, M. Meron, J. Tsipris, A. Naor, V. Ostrovsky, M. Sprinstin and S. Cohen, "Use of thermal and visible imagery for estimating crop water status of irrigated grapevine", *J. Exp. Bot.*, **2007**, *58*, 827-838.
35 M. Fuchs, "Infrared measurement of canopy temperature and detection of plant water stress" *Theor. Appl. Climatol.*, **1990**, *42*, 253-261.
36. I. Leinonen and H. G. Jones, "Combining thermal and visible imagery for estimating canopy temperature and identifying plant stress", *J. Exp. Bot.*, **2004**, *55*, 1423-1431.
37. O. M. Grant, M. M. Chaves and H. G. Jones, "Optimizing thermal imaging as a technique for detecting stomatal closure induced by drought stress under greenhouse conditions", *Physiol. Plant.*, **2006**, *127*, 507-518.
38. O. M. Grant, M. J. Davies, H. Longbottom and C. J. Atkinson, "Irrigation scheduling and irrigation systems: Optimising irrigation efficiency for container ornamental shrubs", *Irrig. Sci.*, **2009**, *27*, 139-153.