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ORIGINAL PAPER

Estimating transpiration dynamics of a low-density litchi orchard using crop coefficients derived from a variable leaf conductance model, canopy cover, and tree height in Northeastern South Africa

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Abstract

Commercial production of litchi (*Litchi chinensis Sonn.*) in arid and semi-arid areas is almost exclusively cultivated with irrigation. In this study we have improved the calculation of the basal crop coefficient ($\mathrm{K_{cb}}$) of litchi for estimating orchard transpiration following the Allen and Pereira (Irrig Sci 28(1):17–34, 2009) (A&P) approach. The original A&P approach calculates $\mathrm{K_{cb}}$ from fixed leaf resistance (r_l) values for specific growth stages, but in reality r_l varies depending on a number of factors such as genotype, environmental conditions, crop growth stages, management, etc. We show that significantly improved $\mathrm{K_{cb}}$, and therefore transpiration estimation, can be obtained using variable values instead of fixed values of r_l in the A&P approach. The original A&P approach uses a typical leaf resistance $(\mathrm{r_{typ}})$ of 100 s/m, a value derived for annual crops. This study derived a specific $\mathrm{r_{typ}}$ of 55 s/m for litchi trees using measured data, whereas r_l was modelled as a variable by Jarvis leaf resistance model. Orchard transpiration was subsequently calculated as the product of the $\mathrm{K_{cb}}$ and the reference evapotranspiration $(\mathrm{ET_o})$. A comparison of calculated and measured transpiration rates resulted in a coefficient of determination of 0.82, a normalized root mean square error of 0.12, a normalized mean absolute error of 0.10, and a Nash-Sutcliffe Efficiency of 0.64. We conclude that the use of the variable r_l and $\mathrm{r_{typ}}$ which are specific to litchi trees gives a more accurate estimation of the transpiration of litchi trees.

Introduction

The availability of sufficient freshwater to sustain crop growth and production is the most important factor undermining irrigated agriculture in arid and semi-arid regions (Alharbi et al. 2024). Many factors limit water availability for irrigation, including climate variability and changes which has resulted in the increasing frequency and severity of droughts in some parts of the world (Nhemachena et al. 2020). Irrigation is crucial to mitigate the adverse effects of climate change-induced droughts, thereby ensuring food and nutritional security, especially for poor communities (Yuan et al. 2024). Litchi (*Litchi sinensis Sonn.*) is an important subtropical/tropical fruit tree species, whose production is essential to alleviating poverty, creating jobs, ensuring food security and providing foreign exchange to countries exporting the fruit (Ghosh 2001; Mitra and Pan 2020). Litchi belongs to the *Sapindaceae* family and is cultivated in more than 20 countries with tropical or subtropical climates (Wei et al. 2013). The fruit is popular in different markets due to

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it's exotic flavour, good taste, and high nutritional value (Li et al. 2013).

Commercial litchi orchards are primarily grown under irrigation and accurate quantitative information is needed on the water use of these trees to guide irrigation decision-making and ensuring sustainable production given the growing resource constraints (Carr and Menzel 2014). Most studies on the water use of litchi treeswere conducted under controlled conditions(Spreer et al. 2007) or in tropical climates (Spohrer et al. 2006). Transpiration is the dominant flux in orchards which depends on crop type, canopy cover, orchard floor management practices (Ntshidi et al. 2021), the wetted fraction of the soil (Ntshidi et al. 2023), among other factors. Accurate orchard transpiration data is critical for developing optimized irrigation schedules, decision support systems, and water allocation models (Ndayakunze et al. 2024). Transpiration is also a critical variable that is often used to evaluate the response of trees to water deficit in irrigation trials (Peng et al. 2022) and in climate change studies (Du et al. 2024). There exists a positive correlation between transpiration and yield. Consequently, some models use transpiration reduction below some potential threshold to model crop yield using water use – yield response functions (Stewart et al. 1977). The correlation between transpiration and yield arises from the fact that the water vapor exiting and CO_2 entering the leaves use the same pathway i.e. via the stomata (Ahmad et al. 2024). However, the water vapor gradient across the stomatal pore is several orders of magnitude greater than that of CO_2 such that slight stomatal closure will reduce transpiration by a greater margin than photosynthesis (Bacon 2004). This is the basis of deficit irrigation strategies, which are common in fruit orchards, aimed at reducing luxurious transpiration and increasing water use efficiency (Chalmers et al. 2004). Several methods have been developed to quantify the transpiration of tree crops. These include different variants of sap flow monitoring methods that rely on injecting heat into the tree (Dangare et al. 2018; Gush et al. 2019). Error margins in sap flow derived transpiration measurements depend on the method used, for example heat pulse method typically produce errors between 5 and 35% (Capurro et al. 2024; Steppe et al. 2010). Other studies have used dyes as tracers of sap ascent through stems (Harris 1961; Kumar et al. 2022). However, this method is limited by several factors such as, (a) it cannot be established whether the dye will travel as far as the sap flow before it deposits on the vessel walls of the plant, and (b) yes will never indicate sap flow velocity changes along a dyed path, but can only show the maximum sap velocity along such a path (Marshall 1958). Transpiration has also been estimated by subtraction of the soil evaporation measurements from the derived whole orchard evapotranspiration (Ding et al. 2013; Puppo et al. 2019). Although these methods are invaluable for estimating orchard transpiration, they are not suited for routine use in orchard irrigation scheduling because they require complex instrumentation, and can be expensive to install and maintain. Instead, the approach reported by the Food and Agricultural Organization (FAO) of the United Nations is widely used in practice (Allen et al. 1998).

While the FAO 56 crop coefficient approach is widely used in water resources management, the method has the limitation that the crop coefficients can not be readily transferable between locations and climatic conditions. Allen and Pereira (2009) developed an alternative method to derive the crop coefficients using readily available data, effectively extending the FAO 56 approach. The method (hereafter referred to as the A&P method) uses a canopy density coefficient ($\mathrm{K_d}$), which is a function of the amount of foliage. $\mathrm{K_{cb}}$ is computed using the fraction of the ground covered by the vegetation $(\mathrm{f_c})$, crop height (h) and a downward adjustment factor called the stomatal sensitivity function ($\mathrm{F_r}$). According to Allen and Pereira (2009), $\mathrm{F_r}$ takes values between 0 and 1, and it is calculated from, among other variables, the ratio of the leaf resistance (r_l) to that of an annual crop set to 100 s/m.

Despite considerable promise, crop coefficients derived using the A&P method have not been consistent (Pereira et al. 2021d). For example, accurate $\mathrm{K_{cb}}$ values with regression coefficients (between calculated and observed values) close to 1.0 and greater than 0.90 were obtained for vegetable crops, field crops and grassland (Pereira et al. 2020, 2021c) but not for tree crops (Taylor et al. 2015; Paço et al. 2019; Mobe et al. 2020; Mashabatu et al. 2023). The A&P method overestimated $\mathrm{K_{cb}}$ values in citrus (Taylor et al. 2015) and apple orchards (Mobe et al. 2020) by between 94 and 127%, respectively. In an attempt to provide a practical solution for application of the A&P approach in different crop types, Pereira et al. (2021c) optimized the values of key parameters in the calculation of $\mathrm{K_{cb}}$, i.e. the canopy transparency ($\mathrm{M_L}$) and $\mathrm{F_r}$ using a numerical search method. The method sought to find $\mathrm{M_L}$ and $\mathrm{F_r}$ values that minimized the differences between the $\mathrm{K_{cb}}$ calculated by the A&P method and those tabulated by Pereira et al. (2021a) and Rallo et al. (2021). In another study of citrus orchards Taylor et al. (2015) replaced the fixed leaf resistance (r_l) with a dynamic resistance that take into account the atmospheric evaporative demand in an algorithm that included the observed $\mathrm{ET_o}$. This approach significantly improved the A&P $\mathrm{K_{cb}}$estimates for citrus, but gave unsatisfactory results for apple orchards (Mobe et al. 2020).

Therefore, the objectives of the current study were, firstly, to quantify the transpiration and its drivers for a mature litchi orchard growing in a semi-arid environment, thereby filling an important information gap. Secondly, we seek to improve the A&P method by implementing a variable rather than a fixed leaf resistance term in the stomatal sensitivity function, given that this resistance changes substantially throughout a typical growing season.

Materials and methods

Study site and plant material

The study was done at Riverside farm in Mpumalanga province in Northeastern South Africa from October 2021 to October 2023 (Fig. 1). The farm is located approximately 6 km north of the town of Malelane (25.447924°S; 31.5547226°E; 144 m above sea level). The orchard was planted in 1970 with the Mauritius litchi cultivar on the Mauritius rootstock. The orchard measured 13.1 hectares, and the trees were planted with a spacing of 13 × 11 m, resulting in a density of approximately 70 trees per hectare. The trees had an average height, measured using a measuring pole, of about 6.3 m and multiple thick branches that branched off close to the ground. The average diameter of the branches was about 0.65 m at <50 cm above the ground. Pruning was done approximately two weeks after harvesting, which typically occured around early to mid November. Soil type up to 1.6 m depth was predominantly silty clay. A soil profile pit (6 m long, 1 m wide and 2 m deep) was dug perpendicular to the tree row using a back-hoe digger. Undisturbed soil cores were collected from 0 to 20 cm, 20–80 cm, 80–120 cm, and 120–160 cm depths within the tree row using stainless steel cylinders (5 cm in diameter and 5 cm in height). Additional undisturbed soil cores were collected from 0 to 50 cm, 50–90 cm, and 90–150 cm between the tree rows. Soil core sampling was replicated five times at each depth and the cylinders containing the soil samples were capped at both ends using plastic lids and stored in a padded cooler box. Analysis of the physical and checmical properties of the soil cores was perfomed by Labserve Analytical Services (Infruitec North Campus, Stellenbosch, South Africa). The field capacity (θ_{FC}) and permanent wilting point (θ_{WP}) were determined by assuming soil water potential of 33 kPa at θ_{FC} and 1500 kPa at θ_{WP}. The average field capacity (θ_{FC}) was approximately 0.45 m^3/m^3 and the permanent wilting point (θ_{WP}) was 0.15 m^3/m^3 for all soil samples.

Data collection

Microclimate

Orchard microclimate was measured using an automatic weather station which was installed in an open space on short grass about 50 m from the orchard. Monitored weather variables included solar radiation, air temperature, relative humidity, windspeed at 2 m height, wind direction and rainfall at hourly intervals. Solar radiation was measured using a Campbell Scientific's Digital Thermopile Pyranometer

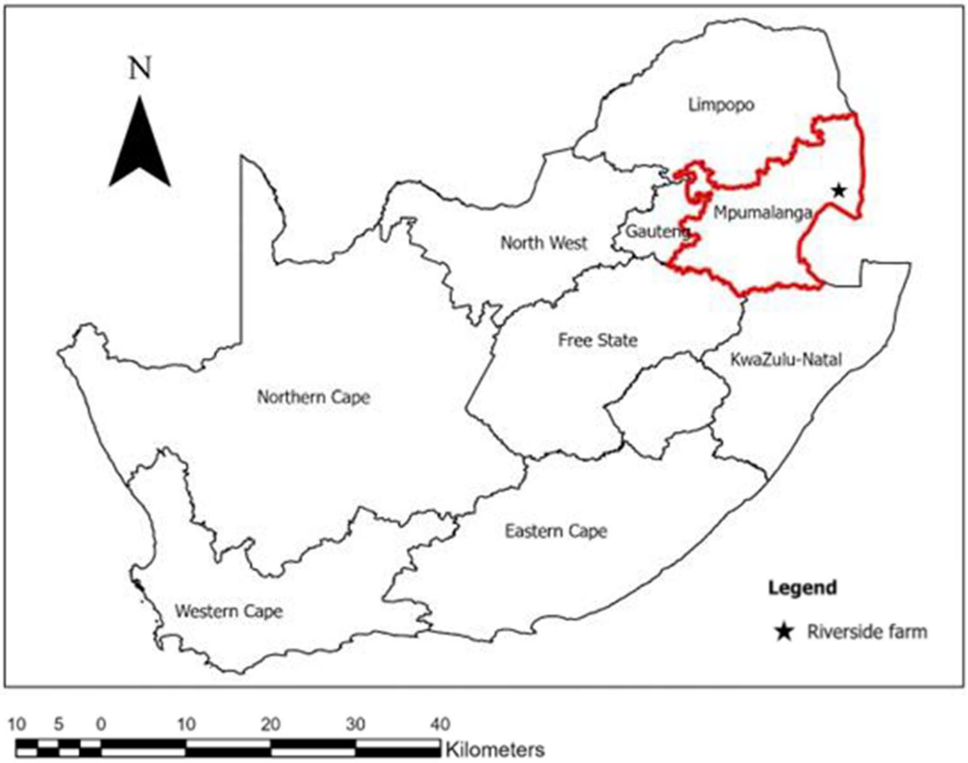


Fig. 1 Location of the study site in the Mpumalanga Province of South Africa

(model: CS320, Campbell Scientific, USA). To avoid self-shading, the CS320 was mounted facing north. This pyranometer measures radiation in the spectral range from 385 to 2105 nm and is highly accurate both in cloudy and clear sky conditions. Air temperature and relative humidity were measured using a digital probe (model: CS215, Campbell Scientific Inc., Logan, UT, USA). Windspeed and direction were measured using a digital sonic anemometer (model: ATMOS-22, METER Group, Pullman, WA, USA). Precipitation was measured using a tipping bucket rain gauge (model TE 525, Campbell Scientific, Utah, USA). All the weather sensors were connected to a CR1000 data logger (Campbell Scientific, Utah, USA) which was programmed to measure every 5 s and to store hourly and daily data. The reference evapotranspiration ($\mathrm{ET_o}$) was calculated using the FAO Penman-Monteith equation for a short grass reference (Allen et al. 1998).

Transpiration, irrigation, and soil moisture measurements

Tree transpiration was measured over two growing seasons (October 2021 to October 2023) using the heat ratio method, HRM (Burgess et al. 2001), which is used to quantify sap flow. Four trees with different stem sizes representative of the tree size distribution in the orchard were identified and instrumented. Three out of the four selected trees had large branches branching close (< 50 cm) to the soil surface. For these trees, the individual branches were instrumented with the sap flow sensors. Whole tree transpiration was determined by summing up the transpiration contributions from the individual branches (Zhang et al. 1997). For each branch, four pairs of T-type thermocouples were installed at four different depths of 10, 20, 30, and 40 mmfrom the bark on the north, south, east, and west sides, respectively, to capture the radial and circumferential variations in sap velocity (Lopez-Bernal et al. 2010). Each pair of thermocouples was installed approximately 0.5 cm equidistant upstream and downstream of a central heating probe (for more detailed experimental setup and theory of the HRM the reader is referred to Section SM1 of the Supplementary Information). The sap flow data were measured and stored hourly using CR1000 data loggers (Campbell Scientific Inc., Logan, UT, USA) connected to AM16/32B multiplexers (Campbell Scientific Inc., Logan, UT, USA). Heat pulse velocity data were corrected for wounding due to the drilling of the trees according to Swanson and Whitfield (1981). The size of the sapwood conducting area was determined by visually inspecting changes in the colour of wood from a slice that was cut from the tree stem.

Irrigation was automated and this was scheduled using capacitance probes (model: Dirk Friedhelm Mercker-DFM, South Africa) that measured the volumetric soil water content at five depths of 30, 60, 100, 120, and 150 cm in the root zone of the trees. The trees were irrigated using microsprinklers with two sprinklers per tree, each delivering 50 L per hour. Typically, irrigation was applied two to three times per week depending on the time of year, and no irrigation was applied during the winter months (May to July). An electronic water flow meter (Model: ARAD Multi-Jet Water Meter, Germiston, South Africa) installed on the irrigation line was used to measure the amount of irrigation. The water flow meter was connected to a CR1000 datalogger which was programmed to record hourly total irrigation volumes.

Volumetric soil moisture data were collected using seven soil moisture probes (model: CS616, Campbell Scientific Inc., Utah, USA). The probes were installed at depths of 30, 60, 100, and 120 cm, respectively, within the tree rows. Three additional probes (Model: CS650, Campbell Scientific Inc., Utah, USA) were installed at depths of 30, 60, and 100 cm between the tree rows. The soil moisture sensors were connected to a CR1000 datalogger which was programmed to store hourly values. All the soil moisture sensors were previously calibrated on similar soil types in South Africa. This was done by taking undisturbed soil samples at all probe measured depths during the dry season when there was no irrigation or rainfall. The bulk density at each of the soil depth was determined and disturbed soil samples were collected over the course of the dry season. Finally, the gravimetric method combined with derived bulk densities was used to estimate the volumetric soil water content. The study concluded that the manufacturer defined calibration for the soil moisture sensors was sufficient (Dzikiti et al. 2018a).

Growth and leaf gas exchange measurements

Leaf area index (LAI: m² of leaf area per m² ground area) was measured every 3 months using a canopy analyser (model LAI2000 canopy analyser, LI-COR, Lincoln, USA). The LAI was measured infrequently because of logistical reasons, given that the study site was about 2000 km away from Stellenbosch University campus. The missing LAI values were interpolated using the cubic spline interpolation method (Liu et al. 2020). The LAI measurements were conducted either on completely overcast days or after sunset when the trees' leaves behaved like blackbodies. The procedure for LAI measurement involved taking a reference measurements for the photosynthetic photon flux density incident on the tree canopies on an open space outside the orchard, followed by five measurements at different locations under the tree canopy. Finally another reference measurement was taken on an open space outside the orchard. All the measurements were conducted using five sensor rings that were characterized by zenith angle centroids located at 7°, 23°, 38°, 53° and 68°. For each tree, the steps were repeated four times using a 180° view cap to screen out the tree trunk influence. The average tree LAI was calculated from LAI measurements on fifteen trees that were close to the centre of the orchard following a diagonal transect across the tree rows. This was done to minimize edge effects and to maximize the LAI footprint.

The leaf stomatal conductance (g_{ST}) was measured using an infrared gas analyser (IRGA) (Model: LI-6800, Li-Cor, Lincoln, Nebraska, USA). These data were measured hourly on tagged, mature, fully expanded, healthy sun-exposed leaves on selected clear days between sunrise and sunset. Twelve leaves were measured on each tree for the four trees that were instrumented with sap flow equipment. Data were collected during the summer (25 and 28 February 2022), spring (24 and 28 November 2022) and winter (22 June 2022 and 8 July 2023) seasons, to capture the seasonal variability in the conductance. In all measurements, the IRGA was programmed to collect data at ambient temperature, 1500 µmol/m²/s photosynthetically active radiation (PAR), which was provided by the internal red/blue LED lamp and 400 µmol/mol constant cuvette CO_2 concentration, which was provided by an external CO_2 canister.

Modelling Litchi orchard transpiration

Calculation of basal crop coefficients ($\mathbf{K_{cb}}$)

When soil water is not limiting, plant transpiration (*T*, mm) can be calculated as:

$$T = \mathrm{K_{cb}} \times \mathrm{ET_o} \tag{1}$$

where $\mathrm{K_{cb}}$ is the basal crop coefficient, which represents the transpiration component of crop evapotranspiration. $\mathrm{ET_o}$ (mm) is the evapotranspiration for a well-irrigated short grass uniformly covering the whole soil surface that is used as a reference (Allen et al. 1998; Pereira et al. 2021b). When water availability is limiting and plants experience stress, $\mathrm{K_{cb}}$ can be adjusted for the stress according to:

$$T = \mathrm{K_s} \times \mathrm{K_{cb}} \times \mathrm{ET_o} \tag{2}$$

where $\mathrm{K_s}$ is the water stress coefficient which ranges between 0 and 1 (Allen et al. 1998). The parameter $\mathrm{K_s}$ is calculated as:

$$\mathrm{K_s} = \left(\frac{\mathrm{TAW} - \mathrm{D}_{\mathrm{r},i}}{\mathrm{TAW} - \mathrm{RAW}}\right) \quad \text{if} \quad \mathrm{D}_{\mathrm{r},i} > \mathrm{RAW} \tag{3a}$$

$$\mathrm{K_s} = 1 \text{ if } \mathrm{D}_{\mathrm{r},i} \leqslant \mathrm{RAW} \tag{3b}$$

$$\mathrm{RAW} = p\mathrm{TAW} \tag{4}$$

Where TAW and RAW are, respectively, the total and readily available soil water (mm) relative to the root zone depth. *p* is the soil water depletion fraction for no water stress, and $\mathrm{D}_{\mathrm{r},i}$ is the soil water depleted from the root zone at the end of day *i* (mm) (Allen et al. 1998). In the current study, *T* for the litchi orchard was calculated using Eq. 2 to account for periods of water stress, and values of 1.0 m and 0.50 were used, respectively for the root zone depth and *p*.

The novelty of the A & P approach is that $\mathrm{K_{cb}}$ can be expressed in terms of the canopy density function ($\mathrm{K_d}$) as:

$$\mathrm{K_{cb}} = \mathrm{K_{c\,min}} + \mathrm{K_d}\left(\mathrm{K_{cb\,full}} - \mathrm{K_{c\,min}}\right) \tag{5}$$

where $\mathrm{K_{cb\,full}}$ is the basal crop coefficient under conditions of full canopy cover, that is LAI > 3.0; $\mathrm{K_{c\,min}}$ is the minimum basal coefficient for bare soil. In this study a value of 0.15 was used for $\mathrm{K_{c\,min}}$, which is a typical value under agricultural conditions (Allen and Pereira 2009; Pereira et al. 2020). The advantage of the A&P approach is that $\mathrm{K_{cb}}$ can be calculated from readily available data. The $\mathrm{K_d}$ was calculated as a function of the mean crop height and the effective vegetation fractional cover (Pereira et al. 2021c) as:

$$\mathrm{K_d} = \min\left(1,\ \mathrm{M_L f_{c\,eff}},\ \mathrm{f_{c\,eff}}^{\left(\frac{1}{1+\mathrm{h}}\right)}\right) \tag{6}$$

where h is the mean crop height, $\mathrm{f_{c\,eff}}$ is the effective vegetation cover, $\mathrm{M_L}$ is a multiplier on $\mathrm{f_{c\,eff}}$ describing the effect of canopy density on shading. The $\mathrm{f_{c\,eff}}$ was calculated at solar noon (1200 h: Local Time = GMT + 2 h) throughout the experimental period as:

$$\mathrm{f_{c\,eff}} = {}^{\mathrm{f_c}}\!/_{\sin(\beta)} \leqslant 1 \tag{7}$$

Where β is the mean angle of the sun above the horizon, $\mathrm{f_c}$ is the fraction of surface covered by vegetation as observed from directly overhead. The fractional cover ($\mathrm{f_c}$) was calculated from the leaf area index as:

$$\mathrm{f_c} = 1 - e^{-k\mathrm{LAI}} \tag{8}$$

where *k* is an extinction coefficient which was taken as 0.6 according to Mobe et al. (2020). The fractional vegetation cover values ranged from 0.78 after pruning to about 0.91 just before harvest. β was calculated as:

$$\beta = \arcsin[\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta) \tag{9}$$

Where parameters ϕ and δ are latitude $(-\pi/2 \leq \phi \leq \pi/2)$ and solar declination in radians respectively (Allen and Pereira 2009). For orchards with low to medium canopy cover, a value of 1.5 is used for $\mathrm{M_L}$, and a value of 2.0 is used for mature orchards with large canopies (Allen and Pereira 2009; Mobe et al. 2020; Paredes et al. 2024; Taylor et al. 2015). We used a value of 2.0 for $\mathrm{M_L}$ in the current study because the litchi trees had large canopies. $\mathrm{K_{cb\ full}}$ is calculated from the variable $\mathrm{F_r}$ regarded as the $\mathrm{K_{cb}}$ adjustment factor through stomatal control, weather parameters, and crop height as:

$$\mathrm{K_{cb\ full}} = \mathrm{F_r}\left(\min\left(1.0 + 0.1\mathrm{h}\ ,\ 1.20\right) + \left[0.04\left(\mathrm{u_2} - 2\right) - 0.004\left(\mathrm{RH_{min}} - 45\right)\right]\left(\frac{\mathrm{h}}{3}\right)^{0.3}\right) \tag{10}$$

where $\mathrm{u_2}$ (m/s) is the mean wind speed measured at 2.0 m height and $\mathrm{RH_{min}}$ is the minimum daily relative humidity (%). $\mathrm{F_r}$ can be calculated using the equation:

$$\mathrm{F_r} = \frac{\Delta + \gamma\left(1 + 0.34\mathrm{u_2}\right)}{\Delta + \gamma\left(1 + \frac{0.34\mathrm{u_2}\mathrm{r}_l}{\mathrm{r_{typ}}}\right)} \tag{11}$$

where Δ (kPa/°C) is the slope of the saturation vapour pressure vs. temperature curve, γ is the psychrometric constant, $\mathrm{u_2}$ is the mean windspeed at 2 m height over grass reference, $\mathrm{r_{typ}}$ (s/m) is the typical leaf resistance and r_l (s/m) is the mean leaf resistance. According to the original A&P method, $\mathrm{r_{typ}}$ is taken as the mean leaf resistance of an annual crop with a value of 100 s/m and the leaf resistance r_l is fixed for the various crop growth stages.

We hypothesized that these two assumptions were likely major sources of uncertainty which resulted in the A&P method overestimating $\mathrm{K_{cb}}$ for most tree crops (Taylor et al. 2015; Mobe et al. 2020; Mashabatu et al. 2023). We therefore proposed two adjustments. Firstly, we recalculated $\mathrm{r_{typ}}$ for the litchi orchard by combining Eqs. 10 and 11 since all the variables were measured in our study at peak canopy cover corresponding to $\mathrm{K_{cb\ full}}$. The parameter $\mathrm{r_{typ}}$ therefore represented the minimum leaf resistance for a litchi orchard. Secondly, the actual leaf resistance r_l at any given time is highly dynamic. It varies with environmental conditions (climate and soil), crop growth stage, crop load, etc. (Gao et al. 2002; Matsumoto et al. 2005; Xu et al. 2021). These variations can occur in a matter of days or even hours. For this reason, we instead proposed using a variable r_l in Eq. 11 that account for day-to-day changes.

Modelling leaf resistance

In this study we modelled the leaf resistance as a function of readily available daily data, such as solar radiation, air temperature and relative humidity which can be accessed from any weather station. Soil water content can be obtained from the farmers' soil moisture probes. The r_l was determined using the equation:

$$r_l = \frac{1}{g_{ST}} \tag{12}$$

where $\mathrm{g_{ST}}$ was the variable stomatal conductance. According toJarvis (1976) the stomatal conductance ($\mathrm{g_{ST}} = 1/r_l$) can be modelled as a function of environmental factors as:

$$\mathrm{g_{ST}} = \mathrm{g_{s\ max}} \times \mathrm{f(R)} \times \mathrm{f(T)} \times \mathrm{f(VPD)} \times \mathrm{f(\theta)} \tag{13}$$

where $\mathrm{g_{ST}}$ is the variable stomatal conductance (m/s), $\mathrm{g_{s\ max}}$ is the maximum conductance, $\mathrm{f(R)}, \mathrm{f(T)}, \mathrm{f(VPD)}$ and $\mathrm{f(\theta)}$ are the solar radiation (R), air temperature (T), vapour pressure deficit of the air (VPD) and volumetric soil water content (θ) stress factors, respectively. These stress factors have values that range between 0 and 1. For the litchi trees, the mathematical form of the stress factors (Dzikiti et al. 2022; Zhang et al. 1997), were expressed as:

$$\mathrm{f(R)} = \frac{\mathrm{R}}{\mathrm{R} + \mathrm{K_r}}$$

where $\mathrm{K_r}$ ($\mathrm{W\ m^{-2}}$) describes the curvature of $\mathrm{f(R)}$.

$$\mathrm{f(T)} = \left(\frac{\mathrm{T} - \mathrm{T_{min}}}{\mathrm{T_{opt}} - \mathrm{T_{min}}}\right) \times \left(\frac{\mathrm{T_{max}} - \mathrm{T}}{\mathrm{T_{max}} - \mathrm{T_{opt}}}\right)^{\left(\frac{\mathrm{T_{max}} - \mathrm{T_{opt}}}{\mathrm{T_{opt}} - \mathrm{T_{min}}}\right)} \tag{15}$$

where $\mathrm{T_{max}}$, $\mathrm{T_{min}}$ and $\mathrm{T_{opt}}$ are the maximum, minimum and optimum temperature for growth of the trees.

$$\mathrm{f(VPD)} = \mathrm{e}^{-\mathrm{K_{vpd}} \times \mathrm{VPD}} \tag{16}$$

where $\mathrm{K_{vpd}}$ describes the influence of the VPD stress factor.

$$f(\theta) = \begin{cases} 1 & \theta \geqslant \theta_{\mathrm{FC}} \\ \left(\frac{\theta - \theta_{\mathrm{WP}}}{\theta_{\mathrm{FC}} - \theta_{\mathrm{WP}}}\right)^{\beta} & \theta_{\mathrm{WP}} < \theta < \theta_{\mathrm{FC}} \\ 0 & \theta \leqslant \theta_{\mathrm{WP}} \end{cases} \quad (17)$$

where β describes the curvature of $f(\theta)$, θ_{FC} is the soil water content at field capacity, and θ_{WP} is soil water content at permanent wilting point. .We calibrated the stomatal conductance model for each season to account for the variations in stomatal responses during the summer, winter and spring seasons. The model was calibrated and validated using data collected over six days collected over the successive seasons. The limited data for the model development was caused by logistical problems as the study site was approximately 2 000 km away from the University campus. The stomatal conductance models for the summer, winter and spring seasons were calibrated using data that was collected on 25 February 2022, 22 June 2022 and 24 November 2022, respectively. The models for the summer, winter and spring seasons were validated using data that was collected on 28 February 2022, 8 July 2023, and 28 November 2022, respectively. Table 1 shows parameters for the stress factors used to calibrate and validate the three models. Model calibration was done using the Marquardt iterative method wherein parameters that minimized the weighted sum of squared differences between the measured and modelled stomatal conductance were selected. All the models were developed using the ModelMaker Software (Cherwell Scientific Ltd, Oxford, UK).

Table 1 Parameter values for the Jarvis model applied to Litchi trees for the winter, spring and summer seasons in Malelane, Mpumalanga province, South Africa

Symbol	Description	Winter	Spring	Summer
β	Describes the curvature of $f(\theta)$ (-)	0.1	1.3	0.1
θ_{FC}	Soil water content at field capacity $(\mathrm{m^3m^{-3}})$	0.45	0.45	0.45
θ_{WP}	Soil water content at permanent wilting point $(\mathrm{m^3m^{-3}})$	0.15	0.15	0.15
$g_{s\,max}$	Maximum stomatal conductance for litchi $\left(\mathrm{mms^{-1}}\right)$	3	3	3
K_{vpd}	Describes the influence of the VPD stress factor	0.35	0.18	0.23
K_r	Describes the curvature of f(R) (in $\mathrm{Wm^{-2}}$)	800	1100	1000
T_{max}	Maximum temperature at which stomata close (?)	45	45	45
T_{min}	Minimum temperature at which stomata close (?)	0	0	0
T_{opt}	Optimum temperature for the growth of the trees (?)	36.5	36.5	36.5

Statistical analysis

The performance of the Jarvis stomatal conductance model and the modelled transpiration was evaluated based on the normalized root mean square error, NRMSE (Barzegar et al. 2016), the normalized mean absolute error, NMAE (Bounoua et al. 2021), the slope, axis intercept (b_o) and coefficient of determination, $\left(\mathrm{R}^2\right)$ (Wu et al. 2023). A value of 0 for NRMSE shows a perfect model prediction, whereas an NRMSE value of 1 indicates a statistical average prediction (Barzegar et al. 2016). A value closer to 0 for NMAE indicates a better model prediction (Bounoua et al. 2021). The R^2 values range from 0 to 1, with an R^2 value of 1 showing a perfect relationship between the observed and predicted data. In contrast, an R^2 value of 0 indicates the absence of statistical correlation between the observed and predicted data (Barzegar et al. 2016).The Nash-Sutcliffe Efficiency (NSE) was used to evaluate the predictive accuracy of the stomatal conductance model(Nash and Sutcliffe 1970) and ranges between $-\infty$ and 1. NSE = 1 is regarded as the optimal value and the NSE values that fall between 0 and 1 are regarded as acceptable levels of performance (Moriasi et al. 2007). It is important to note that NSE $\leq$ 0 shows unacceptable model performance, as this indicates that the mean observed value will be a better predictor than the simulated value (Dzikiti et al. 2018b). Equations for calculating R^2, NRMSE, NMAE and NSE are shown in Supplementary Information SM2, SM3, SM4, and SM5, respectively.

Results

Orchard microclimate

The study area received rainfall in summer, as shown in Figs. 2d and 3. As expected, the daily radiation intensity was maximum in summer (December to February), peaking at approximately 26 MJ/ m^2/d (Fig. 2a). The maximum and minimum air temperatures were 41 °C and 7 °C, respectively (Fig. 2b). The vapour pressure deficit of the air (VPD), peaked at 4 kPa and generally fluctuated between 0.5 kPa and 2 kPa for the rest of the growing season. The reference evapotranspiration $(\mathrm{ET_o})$ peaked at 7.2 mm/d in late spring before the onset of the rainy season. Minimum values fluctuated around 2.0 mm/d on clear days in winter seasons. The mid-summer daily $\mathrm{ET_o}$ values were lower than those recorded in late spring or early autumn because of the high incidence of cloud cover in summer andt his suggested that tree water use would be lower in mid-summer due to the low atmospheric evaporative demand. Exceptionally high rainfall exceeding 70 mm/d was received on 6 January 2022,

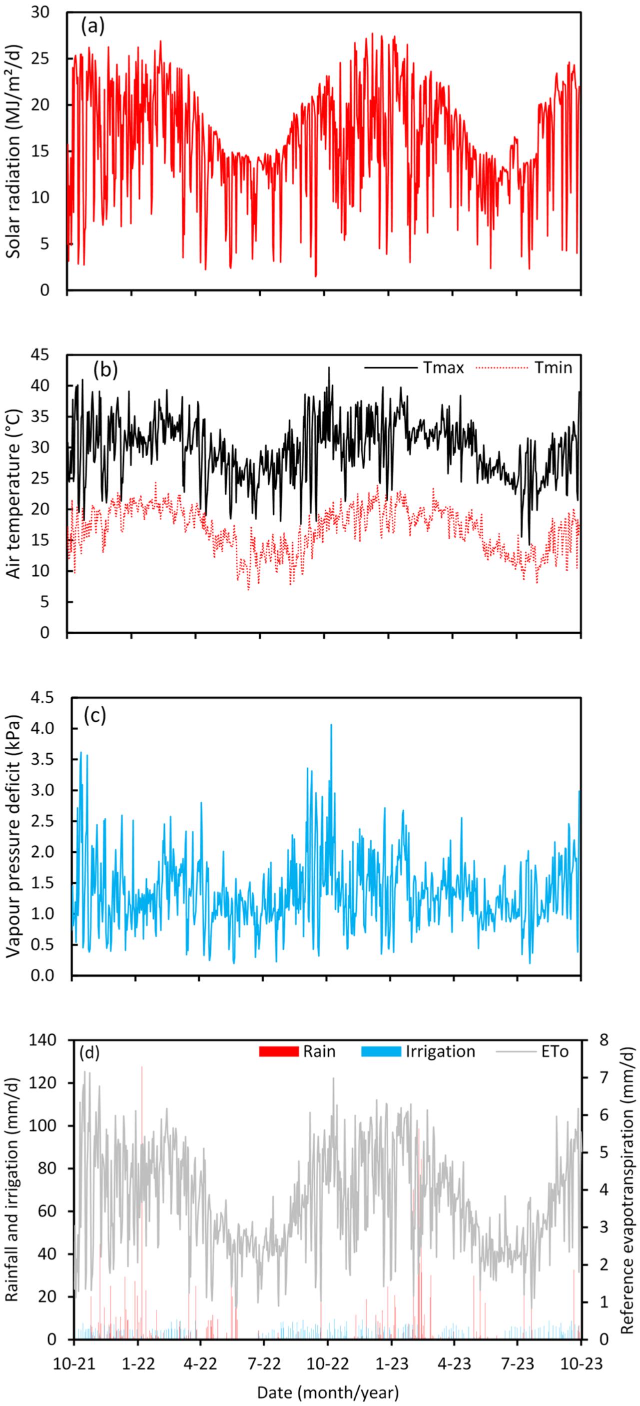


Fig. 2 Daily weather conditions at the experimental site from October 2021 to October 2023: **a** the daily solar radiation, **b** maximum and minimum air temperature, **c** vapour pressure deficit of the air, and **d** reference evapotranspiration

1 February 2023, 9 February 2023 and 12 February 2023 due to storms, and this led to localized flooding. The average annual total rainfall for the two years was 834 mm, and the average annual total reference evapotranspiration was 1 332 mm. An average seasonal irrigation total of 433 mm (4 330 m³/ha/year) was applied in the litchi orchard.

Soil water content and leaf area index

Volumetric soil water content between and within tree row spacings varied throughout the growing seasons (Fig. 3a and b) in response to the rainfall and irrigation events. Sensors installed at at depths of 30, 60 and 100 cm within the tree rows had similar readings for most of the growing season (Fig. 3a) due to the combination of high irrigation levels and rainfall. The volumetric soil water content retrieved from these sensors was close to the field capacity of 0.45 m³/m³. However, the sensor at 120 cm depth showed lower soil moisture content readings which fluctuated around the permanent wilting point and this suggested that the orchard irrigation did not cause deep drainage below the rootzone. Occasional increases in the soil water content at this depth occurred because of heavy rain storms. The soils were drier between the tree rows as the short range microsprinklers did not reach the middle of the tree rows. Spikes in soil water content were associated with incidences of high rainfall. There were also clear differences in the sensor readings at the depths of 30 and 60 cm. (Fig. 3b).

Litchi trees are evergreen, so they maintain a high LAI throughout the year and the monthly average tree leaf area index (LAI) is shown in Fig. 4. The minimum LAI occurred in late November to early December when the trees were pruned. The LAI peaked at about 3.4 in late October, and there was a sharp decline in LAI to about 2.5 after pruning (Fig. 4).

Effect of environmental factors on transpiration

In the current study, a linear relationship between the radiation intensity and tree transpiration was observed (Fig. 5a). High radiation intensities led to higher transpiration rates. The response of the transpiration to the VPD was, however, non-linear (Fig. 5b). Increasing VPD levels increased transpiration rates until a threshold value of about 2.0 kPa. Beyond this limit, further increases in the VPD caused stomata to close, thereby reducing the transpiration rates. While the need to close stomata as the atmospheric evaporative demand increased to avoid the desiccation of the trees is clear, the exact mechanism that leads to stomatal closure due to increases in VPD is not known (Novick et al. 2024). Therefore, we recommend further research on this area. Both solar radiation and VPD have a strong influence on ET_o. Therefore, it is not surprising that there was a non-linear relationship between transpiration and ET_o as shown in Fig. 5c.

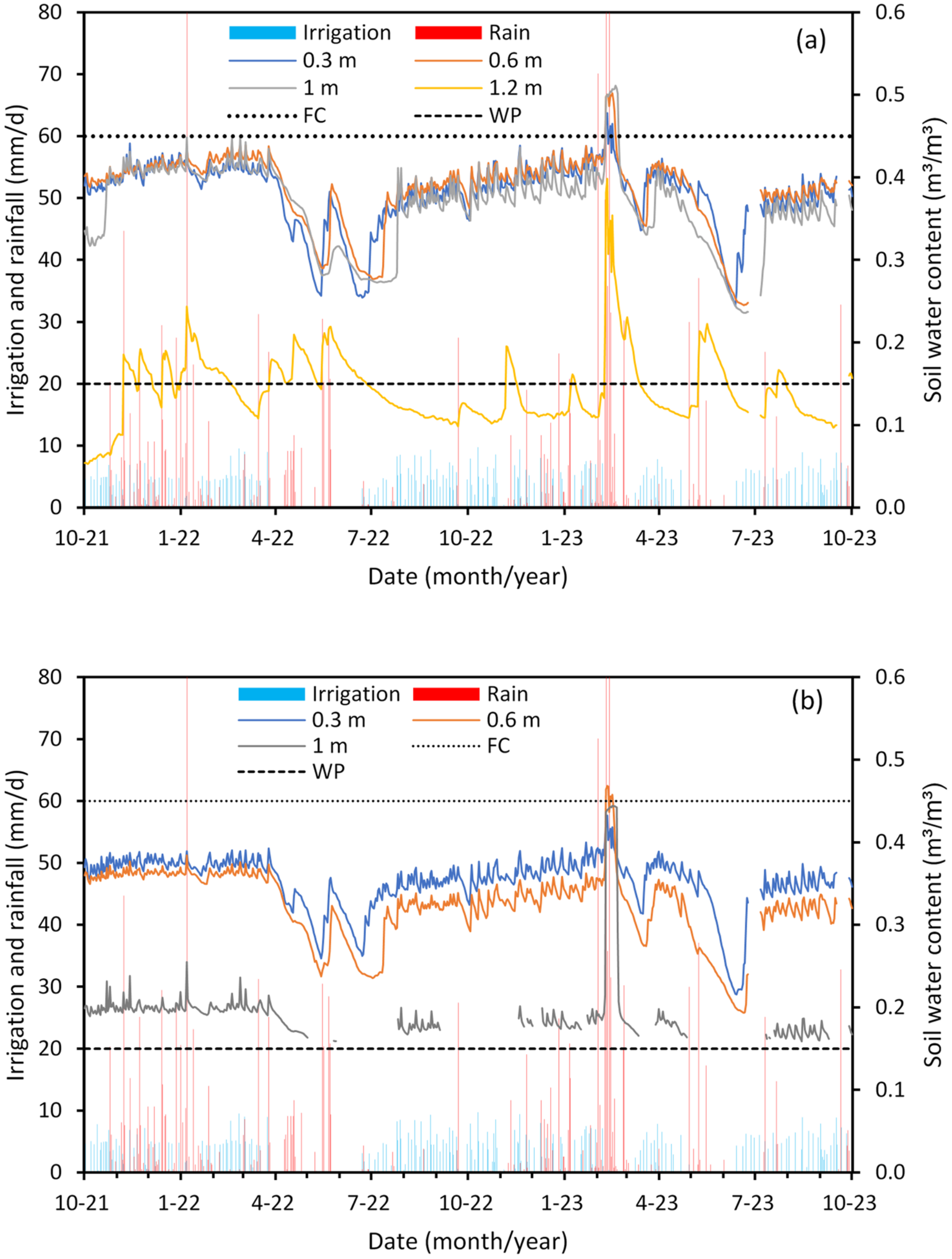


Fig. 3 Soil water content in the root zone of the litchi orchard, as influenced by rainfall/irrigation **a** within tree rows and **b** between tree rows

Stomatal conductance dynamics

The goal of the A&P approach to calculating crop coefficients is to derive these values using readily available data. While the original approach uses fixed stomatal conductance values at specific growth stages, our approach proposes variable stomatal conductance values also using readily available data. In this section, we evaluate the accuracy of theJarvis (1976) stomatal conductance submodel applied to litchi trees. Figure 6a–f show a comparison between the measured and modelled hourly stomatal conductance derived for the winter, spring and summer seasons for the model calibration and validation. The model calibration and validation indicated strong correlations between the measured and modelled values. The model validation produced an R^2 of 0.74, 0.72 and 0.67, respectively, for the winter, spring and summer seasons. The model validation produced an NRMSE of 0.25, 0.23 and 0.22 for the winter, spring, summer, respectively.

Furthermore, the winter, spring and summer stomatal conductance models validation produced an NMAE of 0.23, 0.21 and 0.16, respectively. The model validation gave NSE values of 0.54, 0.47 and 0.48 for the winter, spring and summer, suggesting that the model's predictive accuracy was

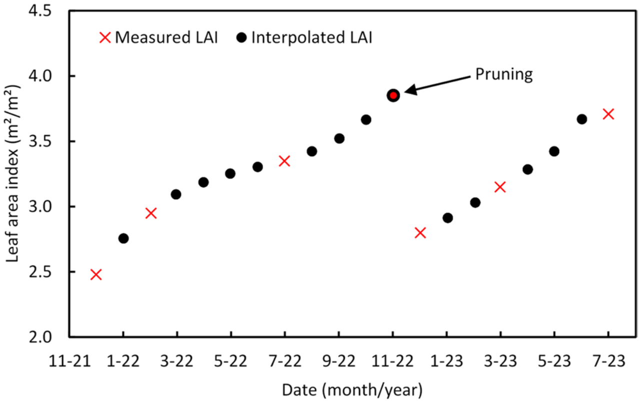


Fig. 4 Measured and interpolated monthly leaf area index (LAI) for the litchi trees used to identify the full-cover conditions when deriving r_{typ} and calculate the fractional vegetation cover

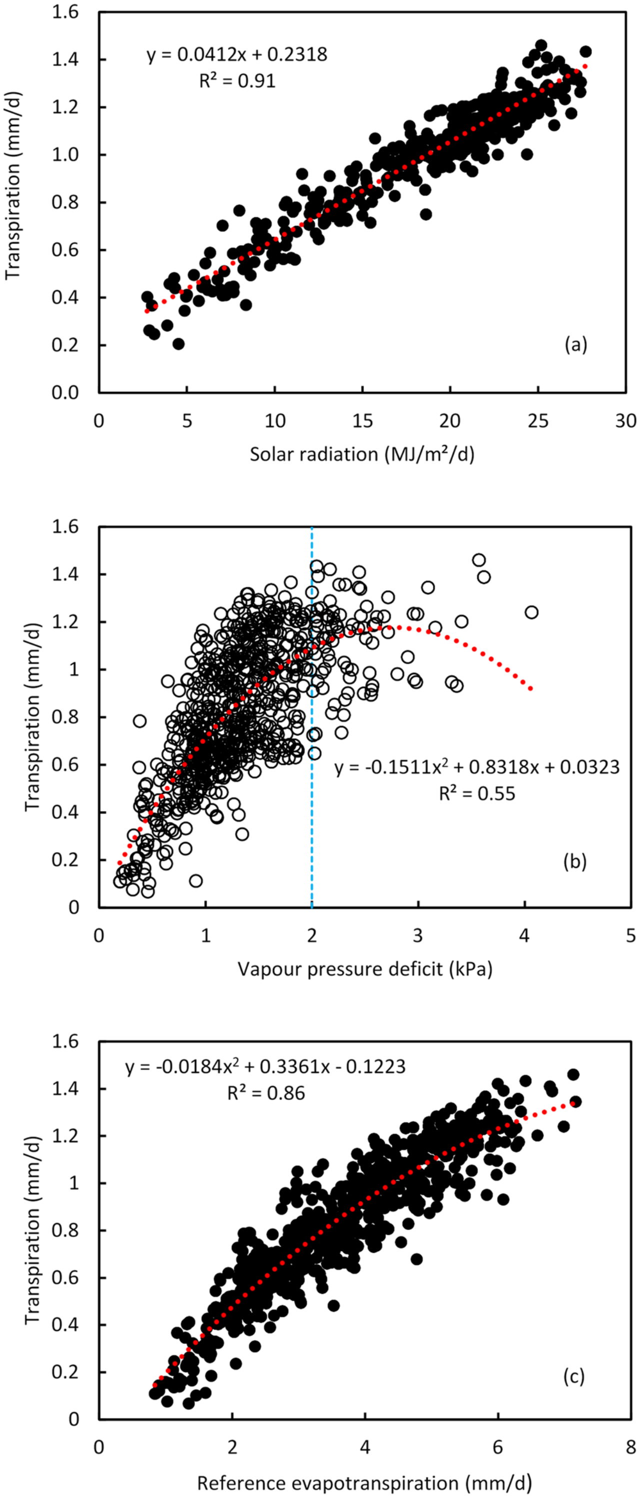


Fig. 5 Litchi transpiration and its drivers namely, **a** solar radiation, **b** vapour pressure deficit (VPD), and **c** reference evapotranspiration

acceptable for all the seasons. Though the model produced acceptable results in this study, it is recommended that the validation procedure be repeated for other litchi orchards under a variety of growing conditions. We proposed to calculate the leaf resistance at the daily time step. The daily leaf resistance was determined by taking the inverse of the daily stomatal conductance. The daily stomatal conductance was calculated by averaging hourly data from 1100 to 1400 h on each day of measurements. A time series of the daily leaf resistance is shown in Fig. 7. There was a consistent trend between measured and modelled values for the litchi leaf resistance (Fig. 7).

Measured and modelled orchard transpiration

The measured maximum daily transpiration by individual trees exceeded 200 L per tree per day (data not shown). However, expressing this in equivalent depth units gave peak transpiration rates around 1.5 mm/d because of the low tree planting density. The measured total annual transpiration was 288 mm for the 2021–2022 season and 315 mm for the 2022–2023 season. The measured average annual litchi transpiration was, therefore, 302 mm or 3 020 m³/ha. The litchi transpiration adjusted to the current orchard tree row spacings gave an average annual of 457 mm (4 570 m³/ha). To model the transpiration rates, we derived a unique value of r_{typ} for litchi using measured variables. We used measured weather and r_l data at maximum K_{cb} (i.e. $K_{cb\ full}$) in Eqs. 9 and 10 for clear days when the trees were well watered, and we got $r_{typ} = 55$ s/m. This value represents the minimum leaf resistance for a litchi tree at full canopy cover and under well-watered conditions. The K_s was calculated daily for the litchi orchard using Eq. 3a, 3b, 4. Applying the K_s, calculated and standard r_{typ} values of 55 s/m and 100 s/m respectively to the litchi orchard data gave K_{cb} values shown in Fig. 8a. The F_r and $K_{cb\ full}$ used to model K_{cb} were calculated on a daily time step throughout the growing season as both parameters depended on daily modelled r_l. The corresponding transpiration (T) is shown in Fig. 8b, where the transpiration was calculated according to

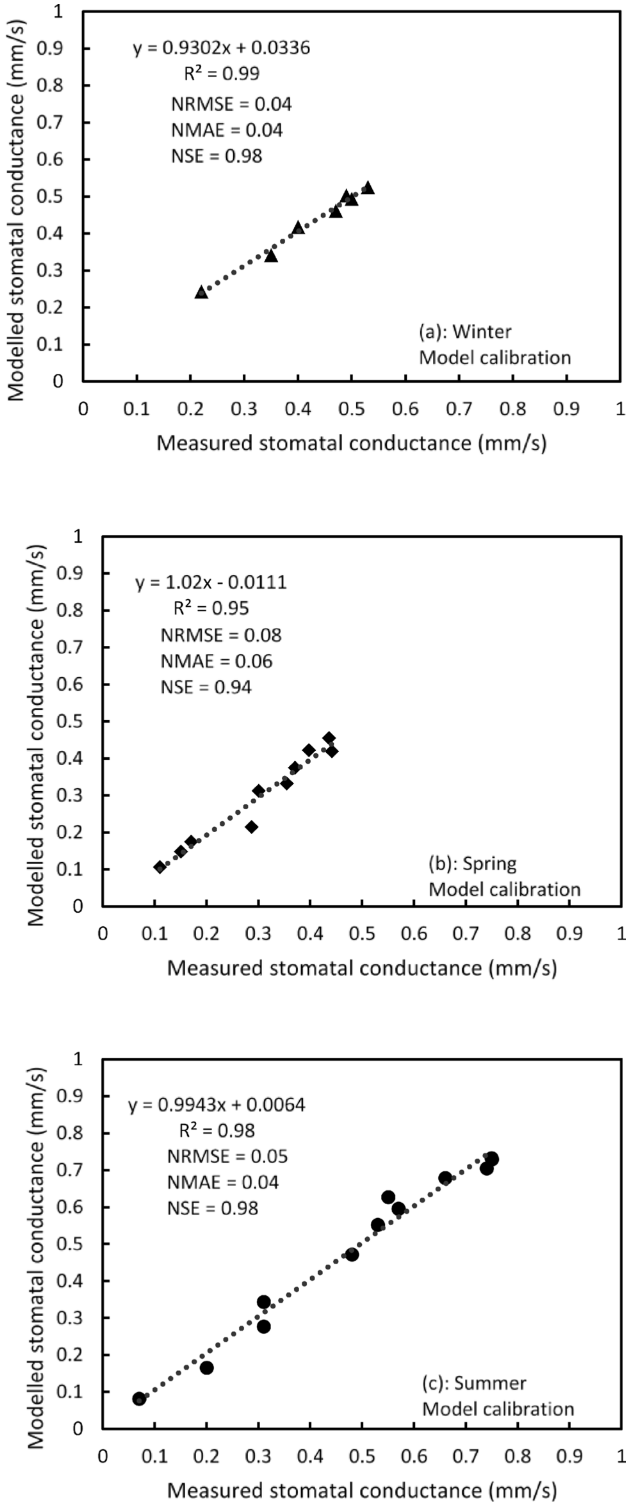


Fig. 6 Relationship between measured and modelled stomatal conductance for litchi trees for **a** winter season calibration, **b** spring season calibration, **c** summer season calibration, **d** winter season validation, **e** spring season validation, and **f** summer season validation

Eq. 2. The $\mathrm{K_{cb}}$ and *T* values modelled using $\mathrm{r_{typ}}$ of 55 s/m had a better fit to the measured values as compared to those obtained using standard $\mathrm{r_{typ}}$ of 100 s/m (Fig. 8a, b). Figure 9 compares the transpiration derived using $\mathrm{r_{typ}}$ of 100 and 55 s/m, respectively. The $\mathrm{r_{typ}}$ = 55 s/m values lie closer to the 1:1 line than the 100 s/m values.

The modelled cumulative total transpiration from 1 October 2021 to 30 September 2022 using $\mathrm{r_{typ}}$=55 s/m and $\mathrm{r_{typ}}$ =100 s/m was 297 mm and 349 mm, respectively, while the measured value was 288 mm. The modelled cumulative total transpiration from 1 October 2022 to 30 September 2023 using $\mathrm{r_{typ}}$=55 s/m and $\mathrm{r_{typ}}$ =100 s/m was 286 mm and 340 mm, respectively, and the measured value was 296 mm. There was an overall 2.9% transpiration overestimation and 3.3% transpiration underestimation in the first year and second year respectively when $\mathrm{r_{typ}}$=55 s/m was used in the transpiration model. Applying $\mathrm{r_{typ}}$ =100 s/m in the transpiration model produced an overall overestimation of 21% and 15% in the first year and second year respectively. Overall, from 1 October 2021 to 30 September 2023, the transpiration model using $\mathrm{r_{typ}}$=55 s/m underestimated measured transpiration by 0.24%, whereas the transpiration model using $\mathrm{r_{typ}}$ =100 s/m overestimated measured transpiration by 18% during the same period (Fig. 10). The comparison between measured and modelled transpiration was performed after excluding the 22 day's transpiration data (from 25 June 2023 to 5 July 2023, and 17 September 2023 to 27 September 2023) when the soil moisture content was not measured due to battery failure, hence the $\mathrm{K_s}$ could not be determined.

Discussion

In this study, we, for the first time, provide accurate quantitative information on transpiration and its drivers for ultra-low density and multi-stemmed litchi orchards under semi-arid subtropical conditions. Water use by tree crops is typically driven by climatic factors e.g. solar radiation, VPD, windspeed etc., and by the available soil moisture. The solar radiation acts as a stimulus for stomatal opening through the response of the stomata to blue light. Solar radiation also provides energy for the evaporation of water from the leaf surface to the overlying air by influencing the leaf's energy balance. Accurate quantitative information on crop water use is critical for the precise management of water resources, especially in arid and semi-arid fruit growing regions (Lascano 2000; Singh et al. 2024). This is particularly important given the threat to water resources posed by climate change and the increasing competition for water among users (Calverley and Walther 2022; Naderi et al. 2024). Precise scheduling of irrigation in this orchard,

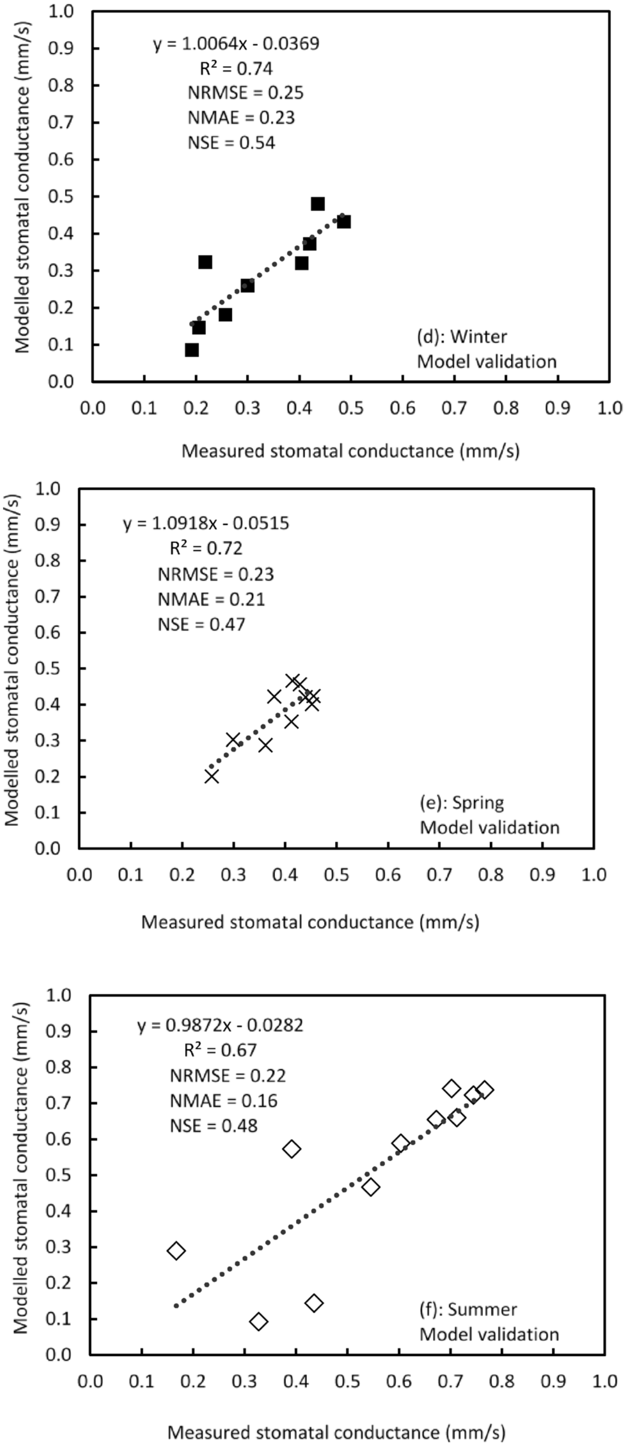


Fig. 6 (continued)

therefore, depends on accurate estimates of the transpiration flux.

While crop coefficients for litchi orchards have been derived in other studies (Menzel et al. 1995; Spohrer et al. 2006), the transferability of these FAO 56 coefficients between orchards needs to be revised, because this introduces errors in water resources management, and often, local measurements and representative crop coefficients have to be derived in new growing regions (Allen and Pereira 2009; Pereira et al. 2021c). In the present study, we contribute to the extension of the FAO-56 approach proposed by Allen and Pereira (2009), focusing on a mature litchi orchard for which little information currently exists. The original A&P method recommends the use of fixed mean leaf resistances during certain growth stages. For litchi, as for other crop types, the duration of the growth stages varies greatly during the growing season depending on environmental conditions and management practices. This is an assumption that we suspect introduces significant errors given the substantial variability in leaf resistance at short intervals (Altieri et al. 2024; Jarvis 1976; Monteith 1995). We therefore proposed an improvement wherein the fixed leaf resistance used in the A&P approach is replaced with a variable leaf resistance. Our results show that this variable leaf resistance, coupled with a r_{typ} for litchi of 55 s/m, yielded significantly improved estimates of K_{cb} and, hence, of litchi orchard transpiration.

To run the model on a daily time scale, the daily leaf resistance was determined by taking the inverse of the daily stomatal conductance. The daily stomatal conductance was calculated by averaging the hourly modelled data from 1100 to 1400 h on each day. The hourly stomatal conductance was computed using the Jarvis-type approach in which the maximum stomatal conductance is moderated by environmental stress factors (Gash et al. 1989; Granier and Loustau 1994; Jarvis 1976; Stewart 1988; Zhang et al. 1997). The selected stress factors required minimum inputs that are readily available to users, namely the daily solar radiation, air temperature, VPD, and soil water content, to maintain the simplicity of the A&P approach. Some studies have shown that parameters for the stomatal conductance models vary with seasons (Damour et al. 2010; Granda et al. 2020; Han et al. 2022). Therefore, the model was separately calibrated for the winter, spring and summer seasons. As expected, the measured stomatal conductance varied with seasons, with the largest range of measurements in summer, during which it changed from about 0.1 to 0.8 mm/s. The seasonal changes in the leaf stomatal conductance are consistent with those reported byHan et al. (2022) in Gansu Province, northwest China. In the current study, the weekly K_{cb} ranged between 0.15 and 0.30 over two years. These values are lower than those reported for litchi orchards in other studies. For example, Paredes et al. (2024) proposed K_{cb} values ranging between 0.7 and 0.9 for litchi with ground cover > 0.3, crop height > 4 m and planting density

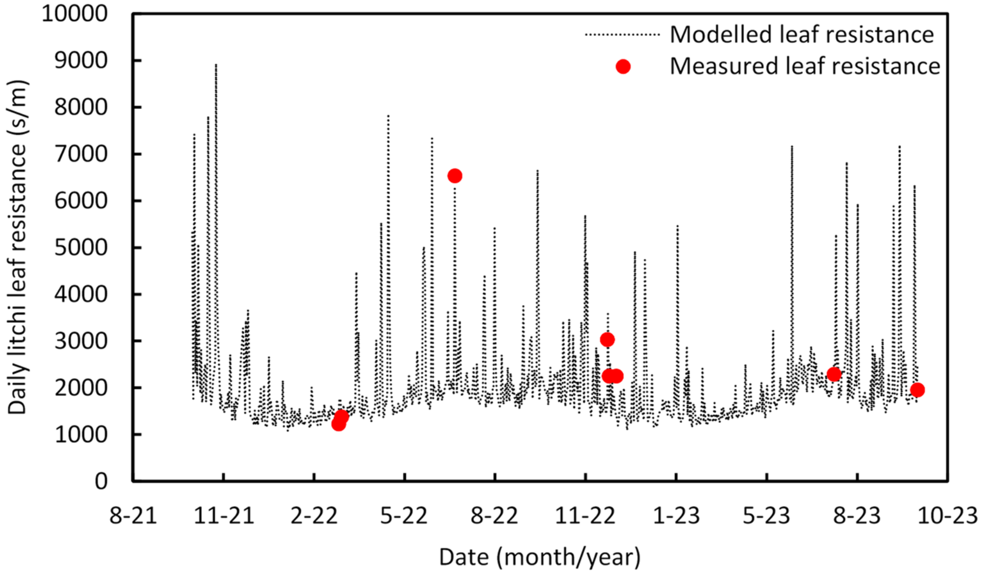


Fig. 7 Measured and modelled daily litchi leaf resistance

of 200–400 plants/ha under vase training. However, the mid-season value of 0.3 obtained in this current study was slightly lower than the K_{cb} value of 0.4 that was proposed for young litchi under vase training (Paredes et al. 2024). In another study, Spohrer et al. (2006) reported that daily K_{cb} ranged between 0.28 and 0.97 for 7 year-old litchi trees in the tropical region of Thailand. Furthermore, they recommended a weekly K_{cb} value of 0.8 to ensure water stress free fruit development for litchi, and this was significantly higher than what was reported in the present study. The reason for the large difference in K_{cb} between those found in the current study and those reported in literature is likely the very low planting density in our study which is characteristic of many litchi orchards in South Africa. The annual total transpiration average in the current study was approximately 3 020 m^3/ha over two years.

Despite the very low orchard scale transpiration rates, the A&P approach was able to estimate these values accurately. This is because the algorithm requires the fractional vegetation cover as an input, and this accounts for the vast differences in planting densities between orchards, hence facilitating the transferability of the crop coefficients. The A&P approach has been incorporated into practical decision support systems for irrigation management in recent years. Examples include the SIMDualKc model(Paço et al. 2012, 2014) and the Inkomati Usuthu Water Management decision support system (Dzikiti et al. 2024), among others. This study demonstrates that the use of the variable leaf resistance in such decision support systems is an option to improve the accuracy of prediction of litchi orchard water use, given that the proposed approach does not add to the complexity of the algorithm.

Conclusion

In this study, measured maximum daily transpiration by individual trees exceeded 200 L/tree/d. However, the Litchi orchard produced a low average annual transpiration when expressed in equivalent depth units (302 mm) because of the low tree planting density (70 trees/ha). The effect of environmental factors on transpiration was investigated, and solar radiation was the strongest driver of litchi transpiration. The correlation of solar radiation and transpiration produced a 0.91 R^2 value. The litchi stomatal conductance was modelled with good accuracy using the Jarvis (1976) model. The model produced R^2 values of 0.74, 0.72 and 0.67, respectively, for the winter, spring and summer seasons. Furthermore, results indicated that the Jarvis-type stomatal conductance model varies with seasons.

An r_{typ} of 55 s/m was derived for litchi using actual $K_{cb\ full}$, weather and measured r_l data to replace the original A&P method r_{typ} value of 100 s/m. A comparison was made on the transpiration derived using r_{typ} of 100 s/m and 55 s/m, respectively. The A&P method using the variable leaf resistance and standard r_{typ} = 100 s/m produced poor model performance when compared to the measured transpiration with NSE = 0.05. On the other hand, the A&P method using the variable mean leaf resistance and r_{typ} = 55 s/m produced a good model performance when compared to the measured transpiration. The model produced an NSE of 0.64 and an overall cumulative error of 0.24% over two years. This substantiates the fact that the improved A&P method, which uses variable mean leaf resistance and r_{typ} = 55 s/m, can accurately model litchi transpiration. Thus, the improved A&P method has a strong potential to be integrated into the precision irrigation decision support systems for water resources management and irrigation scheduling.

Fig. 8 Observed, **a** weekly measured, modelled basal crop coefficients (calculated using improved A&P method which applied variable leaf resistance and r_{typ} of 55 s/m and 100 s/m respectively) for litchi trees and water stress coefficient (K_s), **b** weekly measured and modelled transpiration of litchi trees (calculated using K_{cb} derived using improved A&P method which applied variable leaf resistance and r_{typ} of 55 s/m and 100 s/m respectively)

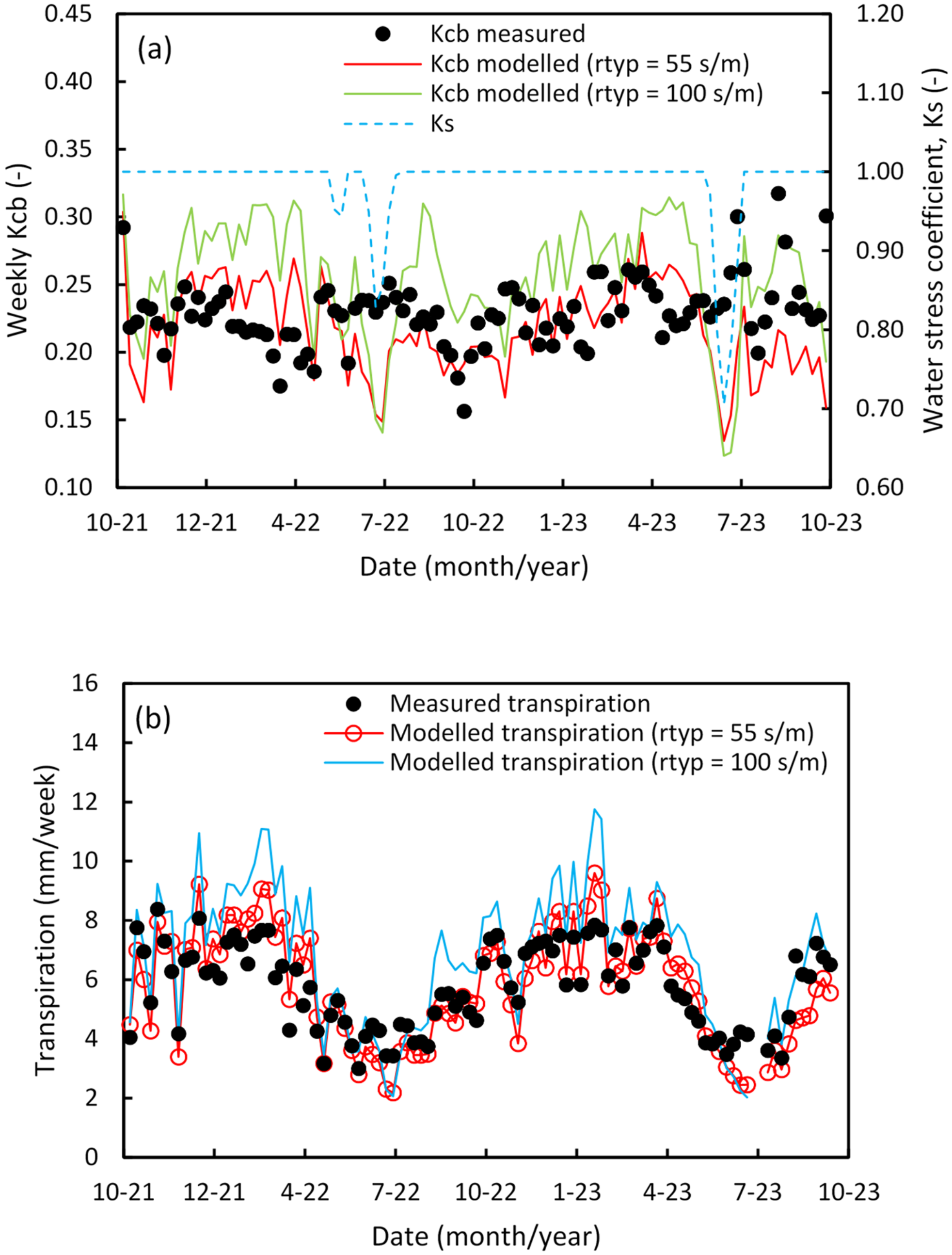


Fig. 9 Comparison between measured and modelled daily transpiration of litchi trees (calculated using improved A&P method which applied the same variable leaf resistance and different r_{typ} values of 100 s/m and 55 s/m, respectively)

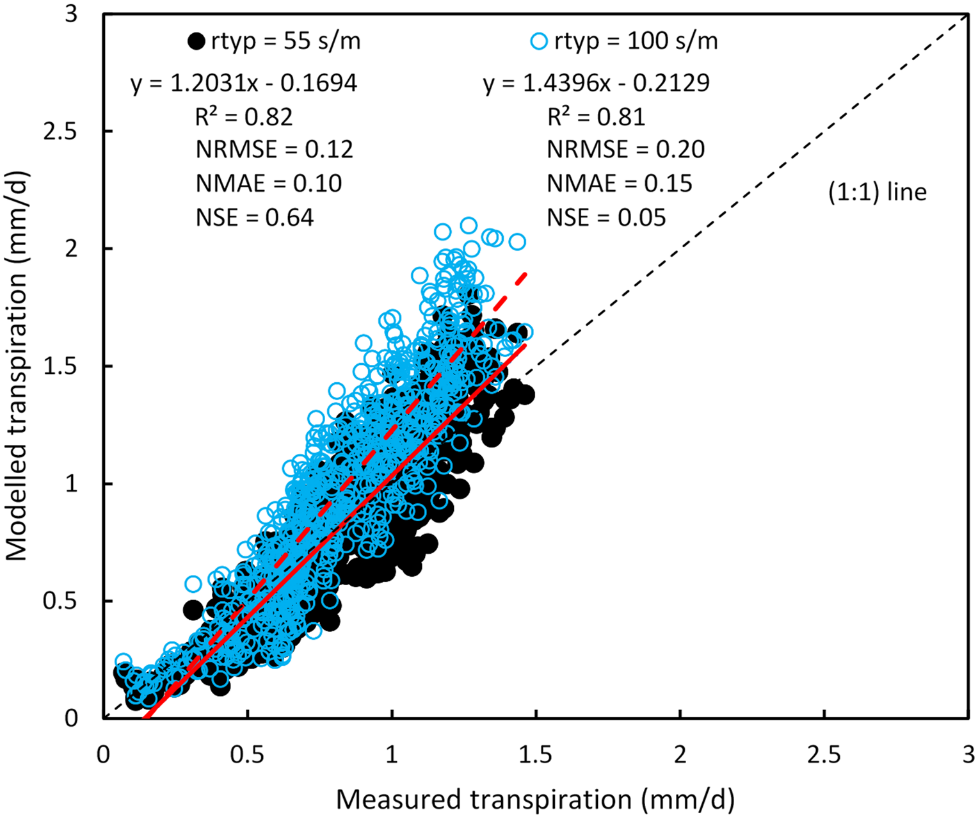
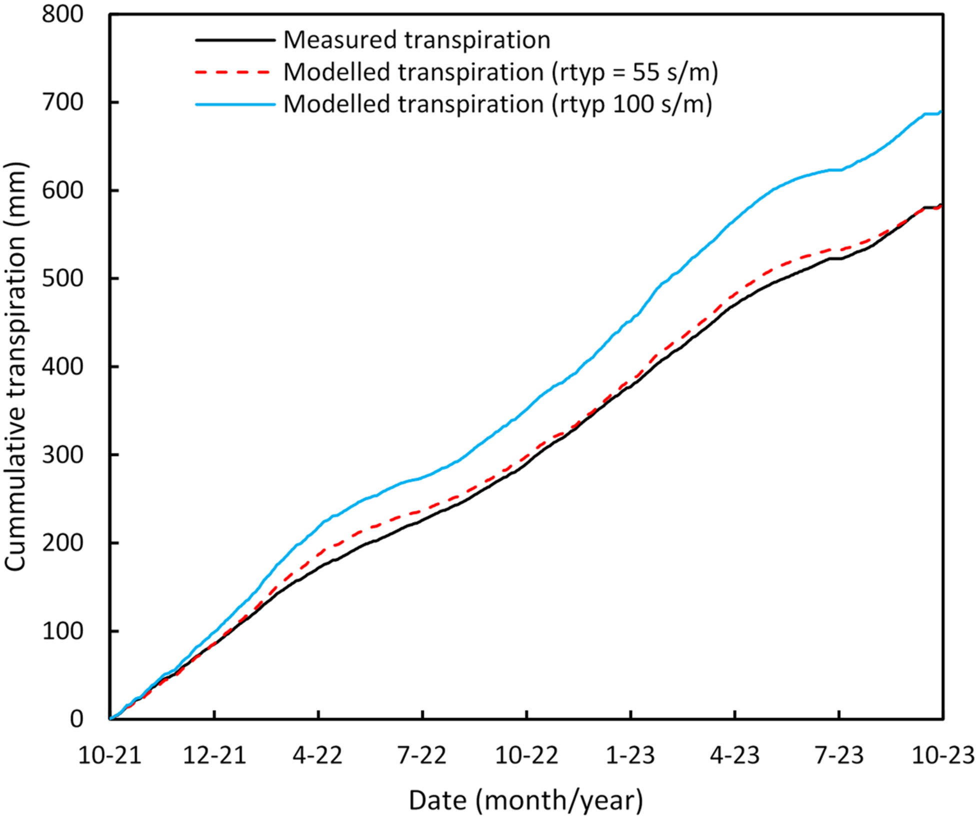


Fig. 10 Observed cumulative measured and modelled transpiration of litchi trees (calculated using improved A&P method which applied variable leaf resistance and r_{typ} of 55 s/m and 100 s/m respectively)



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Author contributions P.D., G.N., J.M., Z.N., S.D. collected the study data; P.D. wrote the main manuscript text, prepared Figs. 2, 3, 4, 5, 6, 7, 8, 9 and 10; Table 1; Z.N. prepared Figure 1; P.C., Z.M., S.D. supervised the study; T.S., S.D. acquired study funding; All authors reviewed the manuscript.

Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare no competing interests.

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