The characterization of the components of the energy and water balance within hedgerow orchards for the verification of a two-dimensional water balance and energy interception model for fruit trees

by

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LIST OF SYMBOLS AND ACRONYMS

List of acronyms

CROPWAT	CROP WATer requirements model (FAO, Rome Italy)
FAO	Food and Agriculture Organization of the United Nations (Rome Italy)
HDS	Heat dissipation sensor
SWB	Soil Water Balance model (University of Pretoria, South Africa)
PEST	ASP Model-Independent Parameter ESTimation (Watermark Numerical Computing, Australia)

List of symbols

a	Half the width of the tree canopy
Acb	Canopy base unit area (m^2 ground)
b	Half the depth of the tree canopy
Cr_{di}	NWM Count ratio for depth interval i
Ct_{Std}	Mean of NWM standard counts
c	Half the height of the tree canopy
D	Drainage
D	Index of agreement of Willmott (1982)
DOY	Day of year
E	Evaporation
ETo	Penman-Monteith grass reference evapotranspiration (mm)
ET_{Gross}	Gross daily evapotranspiration from lysimeters
ET_{lys}	Evapotranspiration determined from lysimeters
FI_{evap}	Canopy cover fraction
FI_{irrig}	Irrigated surface fraction
g	Gravitational constant ($9.8\ m\ s^{-1}$)
h_c	Canopy humidity
hs	Soil surface humidity
Hc	Crop height (m)
Hc_{max}	Maximum crop height (m)
HDS	Heat dissipation sensors
i	Vertical position of a node
I	Infiltration
Ir	Irrigation
j	Horizontal position of a node
k	Extinction coefficient Kcb
K	Hydraulic conductivity ($kg\ s\ m^{-3}$)
Kc	Daily crop coefficient
Kcb	FAO basal crop coefficients
Kc_{max}	Maximum value for Kc following rain or irrigation
K_{PAR}	Canopy extinction coefficient for PAR
K_s	Saturated hydraulic conductivity
K_y	Yield Stress factor
l_j	Distance from tree trunk to NWM access tube j (m)
l_r	Row width (m)
LAb	Leaf area per canopy base unit area (m^2 leaf m^{-2} soil surface)
LAD	Leaf area density (m^2 leaves m^{-3} canopy volume)
LAI	Leaf area index (m^2 leaf area m^{-2} soil surface)
$Ly_{(i)}$	Lysimeter water status for day i (mm)
LyEast	Eastern lysimeter

LyWest	Western lysimetr
M	Molar mass of water (0.018 kg mol^{-1})
MAE	Mean absolute error
MBE	Mass balance error
N	Number of observations
N	Days in growth stage for estimated yield calculation
NIR	Near-infrared radiation (range 0.7 – 3 µm)
NWM	Neutron water meter
PAR	Photosynthetically active radiation (range 0.4 – 0.7 µm)
PE	Potential evaporation (mm)
PET	Potential evapotranspiration (mm)
PT	Potential crop transpiration (mm)
R	Rain (mm)
R	Gas constant (8.314 J K^{-1} mol^{-1})
RD	Root depth (m)
RD_{max}	Maximum root depth (m)
RH	Relative humidity (%)
RH_{min}	Daily minimum relative humidity (%)
RMSE	Root mean square error
Rn	Net radiation (W m^2)
r^2	Coefficient of determination
S	Path length of radiation through the canopy (m)
SI	Stress index
SVP	Saturation vapour pressure (kPa)
SWC	Soil water content (m water m^{-1} soil)
SWD	Soil water deficit (mm)
t	Time (s)
t_j	NWM access tube j
T	Kelvin temperature (^{0}K)
T	Actual crop transpiration (mm)
TDR	Time domain reflectometry
T_{max}	Maximum transpiration rate (mm d^{-1})
U	Wind speed (m s-1)
U_2	Mean daily wind speed at 2 m height (m s^{-1})
Vc	Canopy unit volume (m^{-3})
VP	Vapour pressure (kPa)
VPD	Vapour pressure deficit (kPa)
wt_j	Weighting fractor for NWM access tube j
Y	Estimated yield (Mg ha^{-1})
Y_{pot}	Potential yield (Mg ha^{-1})
Y_{red}	Percentage yield reduction (%)
$Y_{rel(Init)}$	Relative yield for initial stage
$Y_{rel(Dev)}$	Relative yield for development stage
$Y_{rel(Mid)}$	Relative yield for mid-season stage
$Y_{rel(Late)}$	Relative yield for late-season stage
z_o	Distance between the soil surface and the centre of the canopy (m)
z_b	Height at which the base of the canopy is cut off (skirting height) (m)

α	Leaf absorptivity for solar radiation
α_{nir}	Leaf absorptivity for near infrared radiation (0.2)
α_p	Leaf absorptivity for photosynthetically active radiation (0.8)
α_s	Leaf absorptivity for total solar radiation (0.5)
Δd_i	Depth interval for NWM measurements (m)

$\Delta Ly_{(i)}$	Average change in water status for both lysimeters on day i (mm)
$\Delta LyEast_{(i)}$	Change in water status of eastern lysimeter on day i (mm)
$\Delta LyWest_{(i)}$	Change in water status of western lysimeter on day i (mm)
θ	Volumetric water content (m water m^{-1} soil)
θ_{di}	Volumetric water content for depth layer i (m water m^{-1} soil)
θ_{Di}	Water deficit for depth interval i (m water m^{-1} soil)
θ_p	Profile volumetric water content (m water m^{-1} soil)
θ_{ea}	Elevation angle (º).
θ_{fc}	Volumetric soil water content at field capacity (m water m^{-1} soil)
θ_{fcdi}	FC for each depth interval
θ_{pwp}	Volumetric soil water content at permanent wilting point (m water m^{-1} soil)
θ_s	Saturated volumetric water content (m water m^{-1} soil)
ρ_b	Bulk density (Mg m^{-3})
ρ_f	Foliage density (m^2 leaf m^{-3} canopy)
ρ_s	Particle density (Mg m^{-3})
ρ_w	Density of water (1000 kg m^{-3})
τ	Fractional transmission of radiation
τ_d	Daily diffuse transmission coefficient
ϕ	Azimuth angle
Φ	Matric flux potential (kg m^{-1} s^{-1})
ψ	Solar zenith angle (º)
Ψ	Soil water potential (J kg^{-1})
Ψ_e	Air entry potential (J kg^{-1})
Ψ_{fc}	Soil matric potential at field capacity (J kg^{-1})
Ψ_{lm}	Leaf water potential at maximum transpiration, generally occurring in the early afternoon hours (J kg^{-1})
Ψ_m	Soil matric potential (J kg^{-1})
Ψ_{pwp}	Soil matric potential at permanent wilting point (J kg^{-1})

ABSTRACT

Objective of Research

The interest in crop modelling started since the introduction and popularisation of computer technology, which facilitated the dynamic simulation of complex natural systems. In particular, crop growth and soil water balance models for irrigation scheduling are popular at locations where water is a limiting factor for crop production.

In a Water Research Commission project, the soil water balance model (SWB) for irrigation scheduling under full and deficit irrigation was made available. The SWB model is a relatively simple generic crop growth model based on sound physical and physiological principles, (i.e. mechanistic) using daily climatic inputs for daily time-step calculations of the soil-plant-atmosphere water balance to estimate plant growth water use. The SWB model was primarily developed for predicting real-time soil water deficit of field crops with a one-dimensional canopy light interception and water redistribution procedure.

Hedgerow tree crops are planted in widely spaced rows to allow access between trees to carry out necessary management practices (e.g. pest control and harvesting). Distribution of energy is not uniform in widely spaced crops. In addition, localised under tree irrigation is often used for tree crops to reduce system installation costs. This irrigation (micro- or drip) only wets a limited area under the canopy of the trees so that evaporation from the soil surface is also not uniform. One can expect root density to vary with depth as well as with distance between the rows so water uptake for transpiration will also vary in two dimensions. It is also essential to take into account the limited volume of soil wetted under micro-irrigation. If this is not done, the soil capacity will be incorrectly estimated with a standard one-dimensional approach, leading to undesirable over-irrigation in the wetted zone, as well as possible crop stress resulting from a too long an irrigation interval. In order to accurately estimate canopy growth, water balance and yield, it is therefore essential to model canopy radiant interception and soil water balance of hedgerow tree crops in two dimensions and on an hourly time step, based on sound physical principles.

Lack of suitable user-friendly tools to mechanistically describe the two-dimensional energy and soil water balance of tree crops was identified. Due to the importance of fruit crops, on the export as well as local markets, as well as the encouraging results from the initial SWB model, it was decided to improve the SWB model by incorporating a two-dimensional system for use in hedgerow plantings. This thesis reports on the methodology developed to monitor the energy and soil moisture differences within various hedgerows through 24 hour cycles

and the results obtained, as well as the subsequent use of the results to evaluate the 2-dimensional water balance model.

This research was an integral, but independent, part of a larger research thrust, i.e. the development of a two-dimensional fruit tree water balance model that can account for the unique fractional interception of solar radiation associated with hedgerow orchards as opposed to the horizontal planar interception encountered in agronomic crops. The primary objective of this thesis is not the actual programming and mathematical manipulations of the relevant algorithms but to create a reliable data base and then evaluate the model. The primary objective of this thesis was to evaluate the model for deciduous fruit trees using peaches as an example and evaluate the model for evergreen fruit trees using citrus as an example.

Model description

In the overall research thrust two types of model, both predicting crop water requirements on a daily time step, were developed for hedgerow tree crops and included in SWB:

i) A mechanistic two-dimensional energy interception and finite difference, Richards' equation based soil water balance model; and

ii) An FAO-based crop factor model, with a quasi-2D cascading soil water balance model.

For the sake of clarity and completeness, the principles of the models are presented in the thesis and are briefly described in this subsection.

The first model calculates the two-dimensional energy interception for hedgerow fruit trees, based on solar and row orientation, tree size and shape, as well as leaf area density. The two-dimensional soil water redistribution is calculated with a finite difference solution. The two-dimensional energy interception model assumes leaves to be uniformly distributed within an ellipsoid truncated at its base, and radiation penetrating the canopy is attenuated according to Beer's law. This geometry is very versatile as many different shapes can be generated. In order to determine the spatial distribution of soil irradiance across the tree row, the canopy path length through which the radiation must travel to reach a certain point on the soil surface is calculated. Radiation can penetrate neighbouring rows, so two rows on either side of the simulated row are considered.

Beam or direct radiation and diffuse radiation for the PAR (photosynthetically active radiation) and NIR (near-infrared radiation) wavebands are calculated separately, as they interact differently with the canopy. The ratio of actual measured to potential radiation is used to estimate the proportion of direct and diffuse radiation in these two spectral bands.

The attenuation of beam radiation by the canopy is strongly dependent on zenith angle, and, for crops planted in rows, azimuth angle and row orientation will also be crucial. Elevation and azimuth angles are calculated from latitude, solar declination that depends on day of year, and time of day. Before the length of canopy through which radiation penetrates can be calculated, azimuth angle needs to be adjusted to take row orientation into account.

Input data required to run the two-dimensional canopy interception model are: day of year (DOY), latitude, standard meridian, longitude, daily solar radiation, row width and orientation, canopy height and width, bare stem height and distance from the ground to the bottom of the canopy, extinction coefficient, absorptivity and leaf area density.

In order to simulate two-dimensional water movement in the soil, a grid of nodes were established. This divides the soil up into a number of elements. The distances between nodes are selected so that model output can easily be compared to field measured values. Each element has its own physical properties, so this scheme allows variation in soil properties in two dimensions. Symmetry planes are assumed to occur mid-way between two rows on either side of the hedgerow and no water flux is allowed across these planes. The model redistributes water in the soil in two-dimensions using a finite difference solution to Richards' continuity equation for water flow. The aim is to find the matric potentials, which will cause the mass balance error to be negligible. This is done using the Newton-Raphson procedure. Two lower boundary conditions can be chosen in the model: i) gravity drainage for well-drained soils, and ii) zero-flux lower boundary to simulate an impermeable layer.

A precipitation or irrigation in mm is converted to a flux in kg m^{-1} s^{-1} by dividing the time step and multiplying by the horizontal distance over which the water is distributed. The infiltration does not have to be uniform over the surface. Non-uniform infiltration is especially important in very coarse soils where lateral redistribution is likely to be limited, or in the case of micro-irrigation. As with the infiltration flux, evaporation is multiplied by the horizontal distance over which it occurs in order to get an evaporative flux in kg m^{-1} s^{-1}. Potential evapotranspiration (PET) is calculated from weather data using the Penman-Monteith equation and the maximum crop factor after rainfall occurs. PET is then partitioned at the soil surface into potential evaporation and potential transpiration depending on solar orientation, row direction and canopy size, shape and leaf area density. Crop water uptake (transpiration) can either be limited by atmospheric demand or soil-root water supply. Root densities at different soil depths are accounted for in the calculation of root water uptake. The user can specify root depth and the fraction of roots in the wetted volume of soil.

Required inputs for the two-dimensional soil water balance model are: starting and planting dates, altitude, rainfall and irrigation water amounts, as well as maximum and minimum daily temperature. Two points on the water retention function (usually field capacity and permanent wilting point), initial volumetric soil water content and bulk density are required for each soil layer. Soil saturated hydraulic conductivity can also be entered as input for each soil layer, or calculated by the model using the water retention curve. Row distance, wetted diameter of micro-jets or drippers, fraction of roots in the wetted volume of soil as well as distance of the nodes from the tree row are also required as input.

The second, simpler model, based on the FAO crop factor approach, was developed to enable users to predict crop water requirements with limited input data. This model includes a semi-empirical approach for partitioning of aboveground energy, a cascading soil water redistribution that separates the wetted and non-wetted portion of the ground, as well as prediction of crop yields. The FAO-based crop factor procedure was combined with the mechanistic SWB model, thereby still allowing evaporation and transpiration to be modelled separately as supply and demand limited processes. The crop factor model does not grow the canopy mechanistically and therefore the effect of water stress on canopy size is not simulated. The simpler crop factor model should, however, still perform satisfactorily if the estimated canopy cover closely resembles that found in the field.

The following input parameters are required to run the FAO-type crop factor model: planting date, latitude, altitude, maximum and minimum daily air temperatures, FAO crop factors and duration of crop stages. The input data required to run the two-dimensional cascading model are rainfall and irrigation amounts, volumetric soil water content at field capacity and permanent wilting point, as well as initial volumetric soil water content for each soil layer. Row spacing, wetted diameter, distance between micro-irrigators or drippers and the fraction of roots in the wetted volume of soil are also required. Required input data for yield prediction with the FAO model are FAO stress factors for growing stages and potential yield.

Field Trial

Evaluation of the model was carried out for a wide range of conditions (row orientation, period of the year and canopy density). For this purpose, two field trials were set up. The first trial was established in a peach (*Prunus persica* cv Transvaalia) orchard on the lysimeter facilities at Hatfield (Pretoria University experimental farm). This provided a site where detailed observations could be easily recorded to evaluate the SWB model for deciduous trees. The second trial was established in a citrus clementine (*Citrus reticulata* cv. *Nules Clementine*) orchard at the Syferkuil experimental farm of the University of the North. This was the site where measured data were collected to evaluate the SWB model for evergreen trees.

In both field trials, the following field measurements were carried out and used to evaluate the two-dimensional energy interception and soil water balance model:

- i) Weather measurements (temperature and relative humidity, wind speed, solar radiation and rainfall).
- ii) Soil texture, bulk density, penetrometer resistance.
- iii) Volumetric soil water content with neutron water meter and time domain reflectometry (TDR).
- iv) Soil matrix potential with heat dissipation sensors.
- v) Root distribution by taking soil core samples and washing out roots to determine root length.
- vi) Soil irradiance at different distances from the tree row with tube solarimeters.
- v) Leaf area index and density with a LAI-2000 plant canopy analyser.
- vi) Canopy size and row orientation.

In addition, load cell lysimeters were used in the peach orchard at Hatfield in order to measure crop water use.

An additional field trial was carried out at the Hatfield experimental station on Leuceaena (*Leucaena leucocephela*) trees in order to test the two-dimensional radiant interception model for different environmental conditions (tree size and shape as well as row orientation). For the same purpose, two other trials were carried out on two commercial orchards at Brits in Empress Mandarin (*Citrus reticulata* cv. *Empress*) and Delta Valencia (*Citrus sinensis* [L.] cv. Osbeck) orchards. In these field trials, weather data were recorded, soil irradiance across the row was measured with tube solarimeters, as well as leaf area index and density, canopy size and row orientation.

Results

The simple, quasi two-dimensional, cascading soil water balance model was calibrated using data from the peach trial at the Hatfield experimental station. In the process, FAO basal crop coefficients (*Kcb*) were determined for first and second leaf peach trees. The daily crop factor (*Kc*) was calculated using evapotranspiration measurements from the lysimeters and the grass reference evapotranspiration calculated from weather data. The *Kcb* values for the various growth stages were determined by fitting an appropriate line through the lower values of *Kc*, which were taken to reflect the condition where the soil surface was dry (negligible evaporation), subsoil drainage was negligible and there was sufficient water not to restrict transpiration. There was good agreement between predicted and measured daily soil water deficit for water stressed and non-stressed treatments. This was expected since the calibration data came from the trial.

Field measurements in Hatfield also indicated that in hedgerow plantings the whole area across the row must be borne in mind when assessing soil water content. The practice of using single or restricted locality measurements, as utilised in agronomic crops, can be misleading in orchards. The reason for this is the effect of the irrigation distribution and rain interception by the canopy, the variation in radiation interception by the canopy across the row, the irradiance reaching the soil surface as the season progresses, the presence of a grass sod or bare soil in the inter-row region and the root density across the row. In both field trials at Hatfield and Syferkuil, it was found that there are significant amounts of roots in the inter-row region and thus this portion of the rooting volume must not be disregarded when assessing the water balance.

The two-dimensional energy interception and soil evaporation components were evaluated separately. The crucial interactions between the model components were integrated in the validation of the two-dimensional soil water balance model, which uses the energy interception and soil evaporation sub-models to split evaporation and transpiration.

The radiant interception model predictions and the tube solarimeter measured soil irradiance generally gave very good agreement at different distances from the tree row and in different orchards. However, some discrepancies between measurements and model predictions occurred. This was attributed to the presence of trunks and branches shading the tube solarimeters at low leaf area densities, irregularities in the shape of the hedgerow, and non-uniform distribution of leaves within the canopy. In one case the canopy shape differed drastically from that used in the model.

The output obtained with the two-dimensional soil water balance model was compared to independent field measurements in order to evaluate the full SWB two-dimensional model. Volumetric soil water content data collected with the TDR system in the peach and citrus orchards were compared to SWB simulations. Results of model simulations done during drying cycles showed that the surface layer predictions were generally very good. However, in certain situations discrepancies between measurements and simulations were observed, in particular, for deeper soil layers. This could have been due to spatial variability of soil properties, as well as soil disturbance during the installation of TDR probes. It is clear that TDR probes can be used in irrigation scheduling to determine crop water use over certain periods. Caution should, however, be exercised in the interpretation of absolute values of volumetric soil water content obtained from the probes.

Scenario modelling and sensitivity analyses were carried out by varying some input parameters and observing variations in certain output variables. The aim was to show an application of this tool to identify the most suitable management practice in order to maximise water use efficiency. Two case studies were considered for two "virtual" orchards located at different latitudes and in different climates (Kakamas in the Northern Cape and Stellenbosch in the Western Cape). The results of the scenario simulations indicated that, based on the inputs used, the orchards should be planted in a N-S row orientation, a wetted diameter of 0.5 m should be applied when the canopy width is 2 m, in order to minimise water losses through evaporation. As the canopy width increased to 3 m, so the wetted diameter should be increased to 1.5 m. If the wetted diameter is too small, transpiration and thus yield will be reduced.

A sensitivity analysis was also carried out for both case studies varying the fraction of roots in the wetted volume of soil, and observing variations in the output results of evaporation and transpiration. The contribution to crop water uptake from the inter-row volume of soil can be high, in particular under high atmospheric evaporative demand, and this needs to be accounted for in irrigation management in order to maximise rainfall use efficiency in areas of higher summer rainfall.

Conclusions and recommendations

The methodologies developed to measure the temporal and spatial variation in solar radiation and thus the energy distribution within Hedgerow orchards worked well. The methods used to measure the temporal and spatiial variation of the soil water balance also worked well. Thus a very good data set was generated that enabled the sound evaluation of the 2-D SWB model. Thus one can conclude that the two-dimensional energy interception and soil water balance model that was developed in the overall research thrust and included in the Soil Water Balance irrigation scheduling model worked well. The simpler model, based on the FAO crop factor approach and a cascading soil water balance, that was also developed to enable users to predict crop water requirements with a limited set of input data, also gave very satisfactory results.

The FAO-based model and the cascading soil water balance were calibrated for first leaf and second leaf peaches at Hatfield.

The two-dimensional model was fully evaluated for deciduous orchards using data obtained in field trials on peaches and Leucaena (Hatfield). For model validation in evergreen citrus orchards, data obtained in field trials set up at the Syferkuil experimental station (University of the North) and on two commercial farms in Brits were used.

Irregular trunks and branches could cause inaccuracies in predictions of the energy balance. At low leaf area densities, the shade from trunks and branches is not accounted for in the

SWB model. The relative importance of non-symmetric canopy shape as opposed to non-uniform leaf distribution did have an effect but indications where that this was not critical.

The major difficulties encountered in the evaluation of the soil water balance were due to spatial variability of soil properties and disturbance of the soil when the water status monitoring sensors were installed. Careful installation is therefore recommended when using sensors that give localised measurements like those used in this study (heat dissipation sensors and TDR probes).

The successful evaluation of the two-dimensional energy interception and soil water balance model opens the opportunity to develop a useful yield predictor and productivity efficiency measure if one knows the canopy to fruit ratio. This information could also be useful for fruit colour and internal quality research.

As demonstrated with data from the peach trial at Hatfield, soil or cover crops between rows can also have a large effect on the efficient use of rainfall, and this could be further investigated.

The biggest contribution of this model is likely to be the quantification of the contribution that rainfall can make to crop water use by taking the non-irrigated inter-row soil reservoir into account. It is recommended to accurately estimate the root fraction in the wetted and non-wetted volume of soil by digging a trench across the row, taking core soil samples and determining root densities.

The two-dimensional energy interception and finite difference soil water balance model is expected to be more accurate than the cascading soil water balance, due to the sound physical principles on which it is based. The mechanistic detailed approach could give guidance with respect to the magnitude of errors made by using simpler, more empirical approaches. However, the two-dimensional model will also require more input parameters compared to the simpler cascading model. In particular, the most difficult parameters to determine will be the leaf area density for the radiation energy interception part due to the cost of the instrumentation, and the hydraulic conductivity for the soil part due to the specialised knowledge and scientific equipment required. On the other hand, the cascading model requires calibrated FAO crop factors in order to reasonably partition evaporation and transpiration. It would be interesting to compare the cascading and the two-dimensional soil water balance models against field measurements in order to determine the level of accuracy in predictions.

The two-dimensional energy and soil water balance model is primarily meant to be a real-time, irrigation scheduling tool for commercial orchards. Results from this study should guide irrigation scheduling consultants, extension officers and farmers to more efficiently use scarce water resources on high value tree crops. The two-dimensional model, however, can also be used for planning purposes as demonstrated in the scenario simulations. The mechanistic canopy radiation interception routine which has been shown to be very accurate will make it possible to evaluate the effect of row orientation and spacing as well as the effect of wetted diameter and pruning practices on water use

This model also holds tremendous potential as a teaching aid to allow students to do "*what-if ?*" scenario analyses and thus study cause and effect interactions of various orchard designs and practices.