



Modelling Water and Carbon Canopy Fluxes

by

Rhys James Whitley

B.Sc in Applied Physics (Hons)

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Department of Environmental Sciences

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Declaration of Authorship

I, RHYS JAMES WHITLEY, declare that this thesis titled, 'MODELLING WATER AND CARBON CANOPY FLUXES' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
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- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

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The thing the ecologically illiterate don't realize about an ecosystem is that it's a system. A system! A system maintains a certain fluid stability that can be destroyed by a misstep in just one niche. A system has order, a flowing from point to point. If something dams the flow, order collapses. The untrained miss the collapse until too late. That's why the highest function of ecology is the understanding of consequences.

Kynes in "Appendix I: The Ecology of Dune"

Excerpt from Dune by Frank Herbert

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*For Helen, whose patience and love was undying in completing an
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Abbreviations

ANN	Artificial Neural Network
APAR	Absorbed Photosynthetically Active Radiation
BA	Basal Area
CUE	Carbon Use Efficiency
EC	Eddy Covariance
ET	Evapotranspiration
GA	Genetic Algorithm
GENOUD	GENetic Optimisation Using Derivatives
GPP	Gross Primary Productivity
LAI	Leaf Area Index
LUE	Light Use Efficiency
LWP	Leaf Water Potential
ME	Model Efficiency
MJS	Modified Jarvis-Stewart model
MNDR	Multivariate-Nonlinear-Dummy Regression
NPP	Net Primary Productivity
NSW	New South Wales
PAR	Photosynthetically Active Radiation
PEP	Phosphoenolpyruvate
PSD	Particle Size Distribution
RMSE	Root Mean Square Error
RuBisCO	Ribulose Bisphosphate Carboxylase-Oxygenase
RuP₂	Ribulose Bisphosphate

SA	Site-Aaverage model
SOFM	Self Organising Feature Map
SOLO	Self Organising Linear Optimisation
SPA	Soil Plant Atmosphere model
SPAC	Soil Plant Atmosphere Continuum
SS	Site-Specific model
SWC	Soil Water Content
SWP	Soil Water Potential
VPD	Vapour Pressure Deficit
WUE	Water Use Efficiency
WA	Western Australia

Physical Constants

Relative diffusivity of water vapour to CO ₂ in air	a_c	1.56	<i>unitless</i>
Specific heat capacity of the air	c_p	1.013	MJ kg ⁻¹ °C ⁻¹
Gravitational constant	g	9.807	m ² s ⁻¹
Molecular mass of air	M_a	28.96440	g mol ⁻¹
Molecular mass of water	M_w	18.01528	g mol ⁻¹
Atmospheric Pressure	P_a	101300.0	Pa
Universal gas constant	\mathcal{R}	8.1344	J K ⁻¹ mol ⁻¹
Emissivity of the earth's surface	ϵ	0.96	<i>unitless</i>
CO ₂ compensation point @ 25°C	Γ^*	36.5	μmol mol ⁻¹
Psychometric constant	γ	0.066	kPa °C ⁻¹
von Kármán constant	κ	0.41	<i>unitless</i>
Latent heat of vaporisation of water	λ	2.3845	MJ kg ⁻¹
Pi	π	3.14159265	<i>unitless</i>
Density of air	ρ_a	1.204	kg m ⁻³
Density of water	ρ_w	998.2	kg m ⁻³
Stephen-Boltzmann constant	σ	5.6703×10^{-8}	W m ⁻² K ⁻⁴

Symbols

A_{cat}	Catchment area	m^2
A_c	RuBisCO activity-limited assimilation	$\mu\text{mol m}^{-2} \text{s}^{-1}$
A_d	Rate of CO_2 diffusion	$\mu\text{mol m}^{-2} \text{s}^{-1}$
A_g	Gross assimilation	$\mu\text{mol m}^{-2} \text{s}^{-1}$
A_j	Light-limited assimilation	$\mu\text{mol m}^{-2} \text{s}^{-1}$
A_n	Net assimilation	$\mu\text{mol m}^{-2} \text{s}^{-1}$
$C_{\%}$	Percentage of clay (PSD)	%
C_a	Ambient CO_2 concentration	$\mu\text{mol mol}^{-1}$
C_i	Intercellular CO_2 concentration	$\mu\text{mol mol}^{-1}$
C_{leaf}	Leaf capacitance	$\text{mmol m}^{-2} \text{MPa}^{-1}$
C_m	CO_2 concentration in the mesophyll cells	$\mu\text{mol mol}^{-1}$
C_s	CO_2 concentration in the bundle sheath cells	$\mu\text{mol mol}^{-1}$
D_v	Vapour pressure deficit	kPa
D_{vmax}	Daily maximum vapour pressure deficit	kPa
D_{peak}	Position of peak vapour pressure deficit	kPa
D_0	Lohammer constant for D_v	kPa
d_{0p}	Zero plane displacement height	m
d_{root}	Depth of roots	m
d_{soil}	Depth of soil	m
E_0	Potential evaporation	mm hr^{-1}
E_c	Canopy transpiration	mm hr^{-1}
E_{cmax}	Maximum canopy transpiration	mm hr^{-1}
E_s	Soil evaporation	mm hr^{-1}

E_t	Tree transpiration	mm hr ⁻¹
E_T	Evapotranspiration	mm hr ⁻¹
g_a	Aerodynamic conductance	mmol m ⁻² s ⁻¹
g_b	Boundary layer conductance	mmol m ⁻² s ⁻¹
g_{bs}	Bundle sheath conductance	mmol m ⁻² s ⁻¹
g_c	Canopy conductance	mmol m ⁻² s ⁻¹
g_{cmax}	Maximum canopy conductance	mmol m ⁻² s ⁻¹
g_{plant}	Whole plant hydraulic conductance	mmol m ⁻² MPa ⁻¹
g_s	Stomatal conductance to H ₂ O	mmol m ⁻² s ⁻¹
g_{sc}	Stomatal conductance to CO ₂	mmol m ⁻² s ⁻¹
g_{s0}	Residual stomatal conductance	mmol m ⁻² s ⁻¹
g_{smax}	Maximum stomatal conductance	mmol m ⁻² s ⁻¹
g_{smin}	Minimum stomatal conductance	mmol m ⁻² s ⁻¹
g_t	Total conductance to H ₂ O	mmol m ⁻² s ⁻¹
H_s	Relative humidity	%
h	Height of canopy	m
J_e	Potential rate for electron transport	μmol m ⁻² s ⁻¹
J_{max}	Maximum rate for electron transport	μmol m ⁻² s ⁻¹
J_w	Flow of water to the xylem	mm t ⁻¹
K	Soil hydraulic conductivity	MPa m ⁻² s ⁻¹
K_c	Enzyme catalytic activity for CO ₂	μmol mol ⁻¹
K_o	Enzyme catalytic activity for O ₂	μmol mol ⁻¹
K_m	Combined enzyme catalytic activity	μmol mol ⁻¹
K_p	Enzyme catalytic activity for PEP	μmol mol ⁻¹
k_{D_1}	vapour pressure deficit shape parameter 1	kPa
k_{D_2}	vapour pressure deficit shape parameter 2	kPa
k_T	C ₄ first order rate constant for PEP carboxylase	<i>unitless</i>
k_R	Solar radiation constant	W m ⁻²
L	Rate of CO ₂ leakage from the bundle sheath to the mesophyll cells	μmol m ⁻² s ⁻¹
L_{SA}	Specific leaf area	m ² m ⁻²

M_{cj}	C ₄ CO ₂ flux determined by A_c and A_j	$\mu\text{mol m}^{-2} \text{s}^{-1}$
m_{root}	Root biomass	kg m^{-3}
N_f	Total leaf nitrogen content	g m^{-2}
N_{LA}	Nitrogen per leaf area	g m^{-2}
O_i	Intercellular O ₂ concentration	$\mu\text{mol mol}^{-1}$
O_s	O ₂ concentration in the mesophyll cells	$\mu\text{mol mol}^{-1}$
O_s	O ₂ concentration in the bundle sheath cells	$\mu\text{mol mol}^{-1}$
Q_p	Quantum flux density (PAR)	$\mu\text{mol m}^{-2} \text{s}^{-1}$
$R_{a,b}$	Total above and below-ground resistance	$\text{MPa m}^2 \text{s mol}^{-1}$
R_d	Dark respiration	$\mu\text{mol m}^{-2} \text{s}^{-1}$
R_m	Mitochondrial respiration	$\mu\text{mol m}^{-2} \text{s}^{-1}$
R_n	Net radiation	W m^{-2}
R_s	Solar radiation	W m^{-2}
R_{plant}	Plant resistance	$\text{MPa m}^2 \text{s mol}^{-1}$
R_{root}	Root resistance	$\text{MPa m}^2 \text{s mol}^{-1}$
R_{soil}	Soil resistance	$\text{MPa m}^2 \text{s mol}^{-1}$
r_b	Boundary layer resistance	s m^{-1}
r_{root}	Fine root radius	m
r_s	Stomatal resistance	s m^{-1}
$S\%$	Percentage of sand (PSD)	$\%$
S_A	Sapwood area	$\text{m}^2 \text{ha}^{-1}$
T_a	Ambient air temperature	$^\circ\text{C}$
T_{amax}	Daily maximum air temperature	$^\circ\text{C}$
T_l	Leaf temperature	$^\circ\text{C}$
U_z	Windspeed	m s^{-1}
V_{cmax}	Maximum rate for RuBisCO carboxylation	$\mu\text{mol m}^{-2} \text{s}^{-1}$
V_o	Rate for RuBisCO oxygenation	$\mu\text{mol m}^{-2} \text{s}^{-1}$
V_p	Rate for PEP carboxylation	$\mu\text{mol m}^{-2} \text{s}^{-1}$
V_{pr}	PEP regeneration rate	$\mu\text{mol m}^{-2} \text{s}^{-1}$
V_{pmax}	Maximum rate for PEP carboxylation	$\mu\text{mol m}^{-2} \text{s}^{-1}$
\bar{x}_{root}	Mean distance between roots	m

z_h	Height of humidity measurement	m
z_m	Height of wind measurement	m
z_{oh}	Roughness length governing heat transfer	m
z_{om}	Roughness length governing momentum transfer	m
α_j	Quantum yield of whole chain electron transport	mol mol ⁻¹
α_{rf}	Combined constant: Quantum yield and absorbed photons used by the C ₄ reaction process	mol mol ⁻¹
β_e	Proportionality of error	<i>unitless</i>
β_{co}	Co-limitation between light, RuBisCO and CO ₂ limited flux	<i>unitless</i>
Δ	Slope between vapour pressure and temperature	kPa °C ⁻¹
ι_{op}	Stomatal efficiency parameter	<i>unitless</i>
λ_{cw}	Cost of water parameter	μmol mol ⁻¹
Ψ_s	Soil water potential	MPa
Ψ_l	Leaf water potential	MPa
$\Psi_{l_{pd}}$	Pre-dawn leaf water potential	MPa
$\Psi_{l_{min}}$	Minimum leaf water potential	MPa
θ_c	Critical point for transpiration	m ³ m ⁻³
θ_f	Field capacity of the soil	m ³ m ⁻³
θ_j	Shape coefficient for non-rectangular hyperbola	<i>unitless</i>
θ_{tr}	Transition between light-limited and RuBisCO limited CO ₂ flux	<i>unitless</i>
θ_s	Soil water content	m ³ m ⁻³
θ_{sat}	Saturated water content of the soil	m ³ m ⁻³
θ_w	Wilting point for transpiration	m ³ m ⁻³

Abstract

Modelling the water and carbon fluxes from forest canopies provides useful insight into the dynamics of the exchange of water vapour for atmospheric CO₂ and the processes that govern this exchange. The work presented in this thesis aimed to answer four questions related to modelling of canopy gas-exchange. The first two questions involved the development of a simple empirical model of canopy water-use to see whether i) water fluxes from a canopy could be estimated without the need for canopy conductance and ii) could such a model be applied across multiple sites without the need for site-specific calibration? The remaining two questions involved the modification and improvement of a highly mechanistic and complex soil-plant-atmosphere (SPA) continuum model, which was done in order to iii) replicate canopy gas-exchange for a Australian tropical savanna and iv) to improve the simulated leaf gas-exchange process of a SPA model.

A simple empirical model of canopy water-use (E_c), a modified Jarvis-Stewart (MJS) model, was developed in order to circumvent the problem of requiring surface conductance as an input in order to calculate transpiration. This was accomplished by modelling an empirical relationship of the multivariate response of E_c to solar radiation (R_s), vapour pressure deficit (D_v) and soil moisture content (θ_s). The MJS model was shown to provide favourable short- and mid-term (annual) estimates of E_c that only required three more readily available abiotic inputs (R_s , D_v and θ_s) and a small set of site-calibrated model parameters. Predictions of E_c determined from the MJS model were able to replicate the observed data and compared favourably with the established Penman-Monteith (PM) equation and a statistical benchmark created using an artificial neural network (ANN).

In addition to this, the applicability of the MJS model was tested for five disparate Australian woodland sites, where model parameters were calibrated for each individual site and simultaneously for all sites. The result was that while MJS model was able to give a good representation of the measured data using site-specific parameters, using a parameter set that describes an average response of E_c to the environment performed equally well. This was despite each site being comprised of different tree species and occurring over different soil profiles. This showed that the MJS model is partially insensitive to variation in the values of the model parameters and that the number of inputs into the MJS can be

further reduced. The conclusion was that this model is broadly applicable for many sites in temperate Australia and one that can be used as a tool in the management of water resources.

While the MJS model provided a useful management tool, in order to investigate the dynamics of water and carbon gas-exchange from forest canopies, the more complex SPA model of Williams et al. (1996a) was used. While the SPA model has been applied in ecosystems globally with much success, the lack of C₄ photosynthesis has limited its application to savanna ecosystems. Modification of the SPA model was therefore undertaken in order to improve its applicability to savannas through incorporation of C₄ photosynthesis. This was an important improvement as savannas are dominated by C₄ grasses, which contribute significantly to ecosystem water and carbon fluxes. This modification allowed the SPA model to be parameterised to a savanna site in northern Australia, which was simulated over 5 years to replicate measurements of carbon and water fluxes derived from eddy-covariance. The SPA model allowed C₃ and C₄ water and carbon fluxes to be separated and this showed that the C₄ grasses contribute significantly to total savanna productivity (48%), but a much smaller amount to total water-use (23%). Additionally, it was determined the seasonal variation in leaf area index was driving the seasonality in productivity and water-use and the savanna site was determined to be energy-limited (limited by its light interception).

The modification and application of the SPA model to a savanna site highlighted important issues in the way leaf gas-exchange is represented in the model. An investigation into the leaf gas-exchange process handled by SPA showed that there was an imbalance between assimilation and transpiration, as a result of simulated stomatal conductance being increased to unreasonably high levels in order to maximise carbon gain. In order to correct this problem, the modelled gas-exchange was modified to follow the *optimality hypothesis* of Cowan and Farquhar (1977), such that carbon gain is maximised while water lost from the leaf is simultaneously minimised. This improvement was tested in a purely theoretical exercise, where leaf gas-exchange (default and improved schemes) was simulated over a drought. The result of this simulation was that the improved scheme produced a reduction in canopy water-use, while carbon gain remained high and comparable with that of the default scheme.