Evapotranspiration Characteristics of Woody Communities, Natural and Exotic, Across Southern Australia

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Abstract Evapotranspiration characteristics were compiled from a series of measurements made across temperate Australia in woodland and forest. These characterizations of daily rate as a function of fractional plant available water conformed to the law of limiting factors, having an upper bound for the energy limited rate relative to the reference rate given by the Priestley-Taylor formulation. The phase of soil water limitation was expressed as a falling linear trend from the upper plateau to zero plant available water. This decline commenced at a critical intersection point termed the stage of incipient soil water stress that varied between communities but followed a coherent progression according to leaf area index (LAI) of the canopy. For natural communities with LAI between 0.25 and 3.0, the locus of the intersection points followed a linear downward trend with decreasing LAI. Over this range of LAI a shift in the upper bound from 0.80 to 0.57 was associated with an increase in the fractional soil water at incipient stress from 0.30 to 0.95. Thus, the phase of energy limitation was progressively truncated as leaf area decreased. For exotic communities, either woody or herbaceous, sensitivity to LAI was less pronounced and a higher plane of activity evident with values for the critical parameters being 1.0 for the upper bound and fractional soil water of 0.7 at incipient stress. It needs to be noted that these characterizations apply for a non-wetted condition of the canopy and additional estimates of interception loss become necessary for water balance accounting of woody communities. We will examine the ecological implications of differences in evapotranspiration response between contemporary ecosystems and their pristine counterparts for growth and persistence. As part of this comparison, we will demonstrate that this form of characterization offers potential to simulate hydrologic change in a deterministic way for the Australian landscape.

Keywords: Evapotranspiration; Water use; Water balance; Woody ecosystems

1. INTRODUCTION

Across temperate Australia, natural plant communities, frequently dominated by eucalypt species, exercise optimal control on water use for soil water conservation to enable persistence and ecologic stability. In humid regions under forest cover, this control is effective in generating deep drainage for the harvest of high quality water from sustained streamflow. At the other extreme of woodland in semi-arid regions, control on water use rates is effective in minimizing deep drainage thereby avoiding the phenomenon of groundwater rise, a phenomenon that is besetting agricultural land with waterlogging, salinity and soil acidity. A characterization of the differing levels of control on water use in these contrasting regions is undertaken to provide a generalized framework that enables a description of evaporation response by a wide range of woody communities. A comparison of evapotranspiration characteristics of introduced plant communities is undertaken together with a test of our proposition for a generalised framework by accounting for evapotranspiration behaviour of a strip of trees in an agroforestry system.

The data sets for each category of analysis comprise daily values for conditions of non-wetted canopy and cover a wide range of soil water content. This selection for days without rain is designed to remove the confounding influence of interception loss which generally accounts for less than 20% of annual rainfall. A daily time scale is a compromise towards an adequate description of the dynamic control on transpiration and soil evaporation. The daily time scale is compatible with the availability of long term meteorological information, data that are necessary for the application of the derived characteristics in simulation of hydrologic change.

2. METHODS

2.1. Characterizing Evapotranspiration

Ritchie >1981≅developed a dimensionless form of the law of limiting factors to describe the relative daily evapotranspiration rate as a function of the fractional plant available water in the root zone. The relationship takes the form of a ramp function comprising two linear segments to represent the two distinct phases of limitation on the process. The plateau segment represents the energy limiting phase over a range of soil water content during which evapotranspiration rate maintains a constant relationship with a specified reference value of evapotranspiration rate. The falling limb that passes through the origin constitutes evapotranspiration response under soil water limitation covering a specified range of soil water content. The "joint point" at the intersection of the linear segments then defines the salient features for characterizing the plant community, with a specification for the upper bound of evapotranspiration and for the stage of incipient soil water stress. Evaluating the joint point across communities then provides a basis to seek a generalized description in the form of systematic variation in characteristics.

We have opted for the formula given by Priestley and Taylor >1972≅as reference evapotranspiration on the basis of simplicity of application at a daily scale (Ept) and also for a realistic representation of stomatal control by turgid canopies with full ground cover.

$$ŒEpt = 1.26\,(\ni/(\ni+\vartheta))\,R^* \qquad (1)$$

where R^* is the available radiant energy (measured net radiation less ground heat flux less heat storage in vegetation), O is the latent heat of vaporization of water (enabling the switch between mass units to energy units) and $\ni$ and ϑ are psychrometric parameters being respectively the slope of the saturation vapour pressure curve with temperature and the psychrometric constant.

Scaling procedures to define the functional relationships involve determination of the evapotranspiration coefficient, E_T coeff, simply as the ratio of actual evapotranspiration to the Priestley–Taylor value for the designated time scale, generally daily, for which values of R^* are derived from daytime measurements. Setting the independent variable as the fractional volumetric plant available soil water requires the determination of the fractional plant available water within the root zone, W/Wmax. We use measured values of soil water content (obtained using a neutron moisture meter) within the known soil profile for rooting depth and scale these measurements with respect to the observed range of soil water content (this gives rise to Wmax). In the absence of extended measurement, hydraulic properties of the soil profile can be invoked to provide a solution for Wmax in the root zone of known depth.

2.2. Measurement Programme

Field sites for the data array to develop evapotranspiration characteristics were located in Hincks National Park, S.A. (near Cleve) and Kioloa State Forest, N.S.W (Batemans Bay). At both sites, natural woody communities have persisted and maintain stable leaf area (LAI) throughout the year. The mallee community at Hincks has LAI ~ 0.25 and represents the dry end of the climate spectrum whilst the forest community at Kioloa has LAI ~ 3.0 with spotted gum as the dominant species in a humid coastal environment. These data sets are chosen to represent the extremes in LAI for natural woody ecosytems.

Measurement of evapotranspiration at Hincks was made with micrometeorological measurement of latent heat flux (eddy correlation and Bowen ratio methods) in two campaigns (March 1988 and Nov/Dec 1989) to provide 20 days of data with complementary soil water data supplied by gravimetric determinations for the volumetric soil water fraction >Dunin et al., 1999≅. At Kioloa continuous measurement by a weighing lysimeter (1979-1985) yielded 146 days of information for evapotranspiration characterisation supported by weather information and regular soil water data by a neutron moisture meter >Dunin and Aston, 1984≅

The community for testing the scheme to generalize characteristics was at 'Ucarro' near Katanning, WA, and comprised a 10 year old stand of 20 m wide strips of trees planted on the contour in extended lines with four eucalypt species that have an overall LAI of 1.4 for the strip >White et al., 2001≅ Heat pulse measurements offered continuous measurement of transpiration rate and soil water balance measurement with a neutron moisture meter enabled a dissection for interception loss and also for direct soil evaporation. Measurement of exotic communities comprised soil water balance measurements for a blue gum community in Tasmania. >Battaglia and Sands, 1997≅ Widely ranging agricultural communities as crop and pasture >Ward and Dunin, 2001≅have been evaluated using both soil water balance and direct assessment of evapotranspiration by micrometeorological techniques.

3. RESULTS

3.1. Evapotranspiration Response

For conditions of high soil water content, diurnal progressions of latent heat flux displayed a sinusoidal pattern for both communities in following the course of radiant energy input (Figure 1a and b). The higher fluxes by the Kioloa community both in absolute magnitude and relative to the energy input, (E_T coeff. = ŒE/ŒEpt in Figure 1), produced a daily value of 4.28 mm that was ~30% greater than the mallee community at Hincks (3.25 mm) which was in receipt of greater input (25%) of available radiant energy. The observed differences in values for latent heat flux and in the respective daily vales of evapotranspiration are marginal when considered in the context of a tenfold difference in leaf area index (LAI) and indicates a compensating response in direct evaporation from soil under the mallee community. A simple analysis to partition the latent

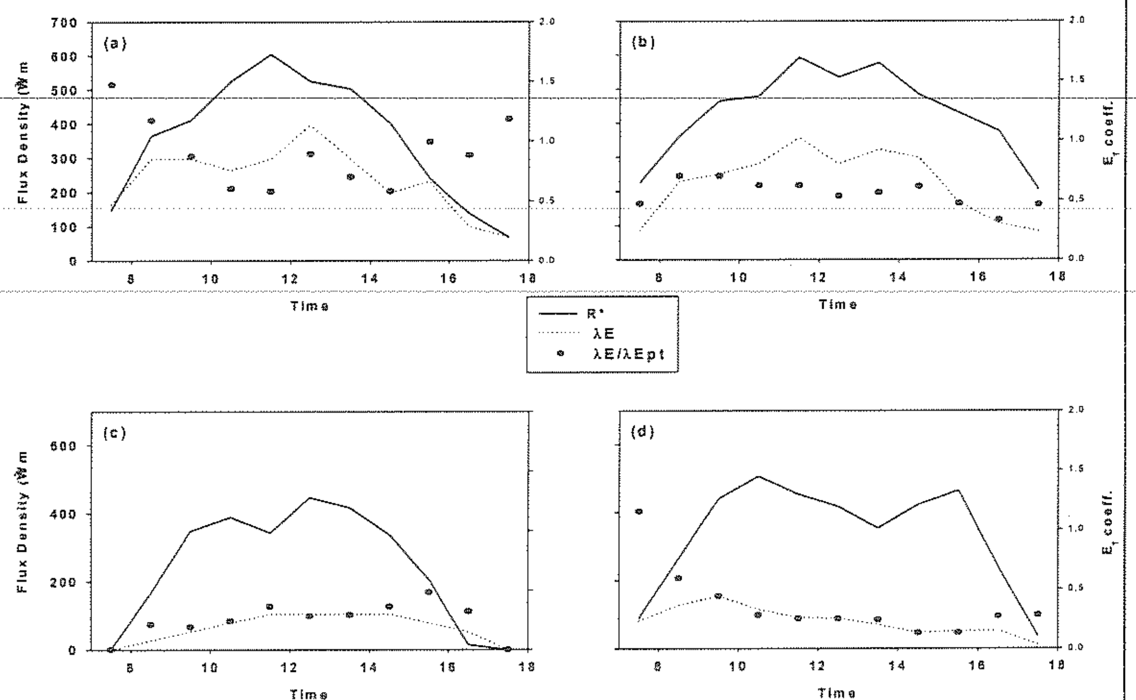

Figure 1. Diurnal progressions of available radiant energy (R*) and latent heat flux (ŒE) and E_T coeff (ŒE /ŒEpt) at Kioloa ((a) and (c)) and Hincks ((b) and (d)) with high initial soil water content ((a) and (b)) and low soil water content ((c) and (d)).

heat flux reveals that direct evaporation from soil under mallee comprised more than 50% of the total daily value for that day.

Under dry conditions there was little to distinguish between the communities in terms of diurnal patterns and totals of ~1mm for daily evapotranspiration. The generally flat diurnal responses indicated a loss of sensitivity to radiation input. The major deviation to these flat responses was apparent in the progression of E_T coeff. , early morning, at Hincks. High values of the coefficient were associated with evaporation of intercepted water following 0.2 mm dewfall.

LAI as a determinant of evapotranspiration rate was most pronounced at high soil water content in influencing the partitioning between soil evaporation and transpiration, leading to increased values of E_T coeff as the proportion of transpiration increased. Foreshadowing data analysis at a daily scale (Figures 2 and 3) the effect of LAI on the upper bound of E for a given community can be expressed as a coherent trend of E_T coeff (E/Ept) as an exponential relationship.

$$E_T \text{ coeff} = 0.55\ e^{-0.125LAI} \qquad (2)$$

As soil water decreases so the governing role of leaf area becomes less important.

3.2. Drying Sequences

Four time series of daily evapotranspiration (Figure 2) are provided to explore differences in the patterns of E_T coeff during drying sequences as influenced by initial soil water and by LAI. Each sequence experienced progressive daily depletion of soil water with the only rainfall of 1.6 mm recorded on Dec 5 in Figure 2(a), and dewfall, registered on some days in each sequence was less than 0.2 mm for each day of its occurrence.

At high initial soil water, patterns of E_T coeff differed between the study communities (Figures 2 (a) and (b)). High LAI at Kioloa was instrumental in the maintenance of high values of E_T coeff generally between 0.7 and 0.8 in the sequence with variable

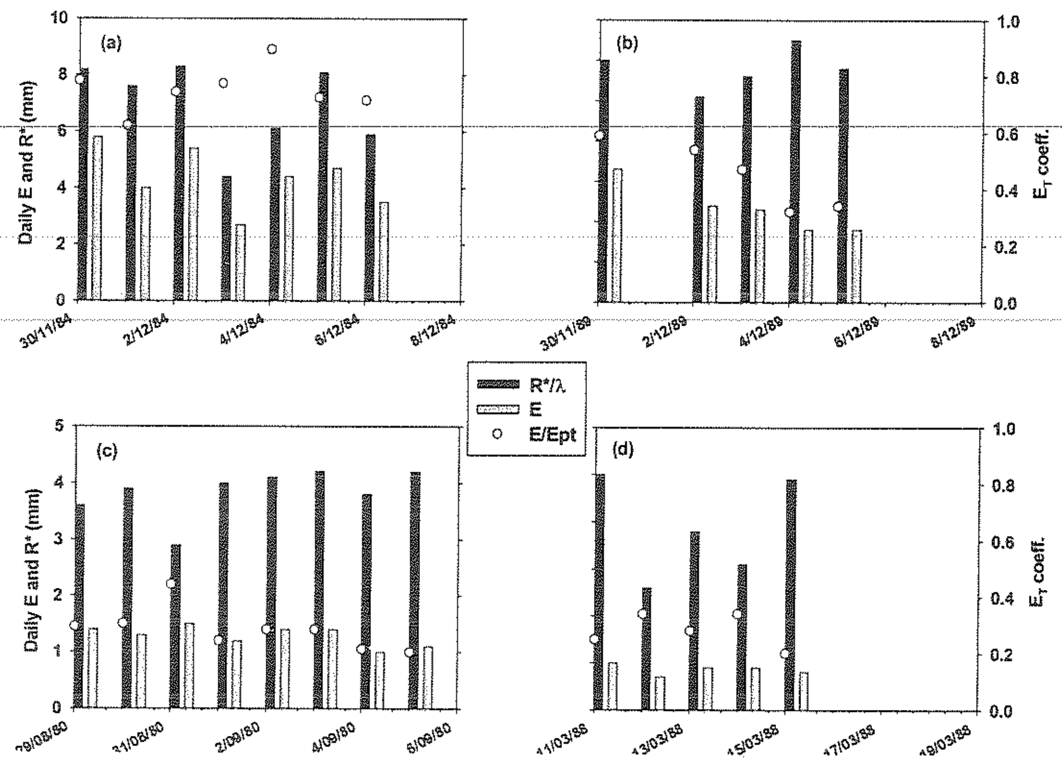

Figure 2. Time series of drying sequences of daily evapotranspiration (E) at Kioloa ((a) and (c)) and for mallee at Hincks ((b) and (d)) with high initial soil water content ((a) and (b)) and low soil water content ((c) and (d)), indicating the regime of available radiant energy in each sequence (R*/O) and the time course of E_T coeff (E/Ept).

radiation inputs; the outlier of 0.89 on Dec 5 was associated with interception loss of the rain of 1.6 mm. The corresponding sequence for low LAI at Hincks displayed a progressive fall in E_T coeff from its maximum value of 0.57 on day 1 during a sunny sequence with only minor variation in daytime radiation.

At low soil water content there was little to distinguish between communities in absolute magnitude of E of ~1 mm/day and E_T coeff tending towards 0.2 (Figures 2(c) and (d)). The noisy pattern of E_T coeff in Figure2 (d) can be attributed to uncertainty in flux evaluation by micrometeorological methods at high values of the Bowen ratio that prevailed at this stage.

The LAI effect on patterns of E_T coeff at high soil water content is attributable to its role in partitioning vapour flux between transpiration and soil evaporation. The phase of energy limitation in terms of the operative range of soil water content is reduced as the proportion of the total flux as soil evaporation increases. Thus, in using a ramp function for evapotranspiration response LAI becomes the major determinant for setting the joint point and definition of a joint point provides adequate characterisation of the combined controls on transpiration and soil evaporation of the plant community with stable leaf area.

3.3. Evapotranspiration Characteristics

The derived characteristics for natural forest at Kioloa and mallee woodland at Hincks are shown

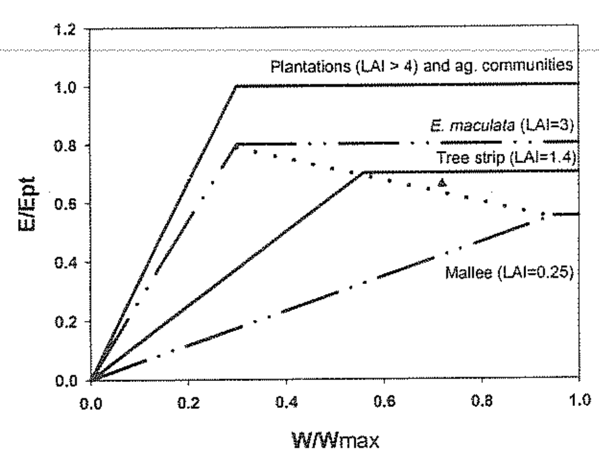

Figure 3. Relative evapotranspiration response, E/Ept, as a function of plant available water (W/Wmax) in the root zone of four nominated plant communities. ▲ denotes predicted joint point for tree strip.

(Figure 3) with the "joint point" for Kioloa having values of 0.30 for W/Wmax and 0.80 for E_T coeff and that at Hincks having respective values of 0.95 and 0.57. The linear scanning trajectory (shown as the dotted line) joining these "joint points" purports to indicate the locus of these "joint points" across the intermediate range of LAI between the extremes of the two study sites. The test community at "Ucarro" describing the evapotranspiration characteristics of contour tree strips with LAI of 1.4 is included with the ramp function derived from measured daily values. Using eq. 2, the predicted "joint point" is shown with coordinates of 0.72 (W/Wmax) and 0.66 (E_T coeff). The corresponding values for these coordinates shown of the curve are 0.54 and, 0.71. The correspondence between predicted and actual may be judged as reasonable but nonetheless, it suggests that refinement of eq. 2 may be called for through the analysis of more data from natural communities as they become available.

The uppermost response function relates to plantations and agricultural communities both of which share a common "joint point" of 0.70 and 1.00. Plantations with high LAI conform to the Priestley-Taylor estimate for the upper bound. Similarly, a range of herbaceous plant communities accords with these critical values for the joint point but without any specification for LAI. These herbaceous communities differ from woody communities in being insensitive to LAI. Radiant energy not intercepted by foliage for transpiration is equally effective for direct evaporation from moist soil. This complementarity between transpiration and soil evaporation with herbaceous communities is achieved at moderate demand such as applies for most of the temperate growing season (up to Ept values of 4 mm/day).

4. DISCUSSION

Characterizing evapotranspiration response as a ramp function provides a basis to discriminate between plant communities in terms of their critical "joint points". Although this linearized description masks a subtle shift in the "joint point" with atmospheric demand, the form is sufficiently robust to articulate the function of natural communities in conserving soil water to ensure persistence. As the climate becomes drier, control of soil water loss in natural communities increases progressively. This is achieved through a strategy of reducing stable leaf area that has the effect of lowering the upper bound of evapotranspiration as well as reducing the time interval over which this upper bound operates after rain. By comparison, exotics utilize water rapidly while soil water is abundant to achieve high growth rates. The hydrologic penalty of diminished persistence is compromised root development and reduced capacity to contain rain excesses leading to accelerated deep drainage and deleterious consequences of rising watertables.

The soil evaporation process is acknowledged as being important in defining the "joint point" for a particular community. Following the arguments of Denmead et al. >1996≅ it can be demonstrated that the absolute magnitude of soil evaporation under canopies of natural communities rates as 50 – 75% of that experienced under crops at equivalent leaf area. Suppression of soil evaporation from the floor of woody communities can be attributed to factors such as litter mulches and radiation attenuation at the soil surface by woody structure of the over-storey. Inhibited soil evaporation leads to sensitivity to LAI as expressed in the magnitude and duration of the upper bound of evapotranspiration from natural communities. By comparison, inhibition of soil evaporation from disturbed cropland is notably absent.

Adaptation of natural ecosystems to environmental stress is apparent with soil water rationing to extend periods of water use. This is implicit in the proposition that natural ecosystems adjust their stable leaf area according to annual rainfall >Specht 1972; Hatton et al., 1998≅ Such a proposition serves as a surrogate for LAI prediction of climax ecosystems to be included in functions such as eq.2 for "a priori" modelling of hydrologic change.

5. CONCLUSIONS

Using a ramp function to describe evapotranspiration response of natural woody plant communities across a gradient in rainfall, a coherent trend with LAI was established for the critical characteristics that represented the upper bound of evapotranspiration rate and the stage of incipient soil water stress.

Both woody and herbaceous exotic plant communities shared a common set of characteristics that were insensitive to LAI but which explained enhanced growth rates of these ecosystems.

6. ACKNOWLEDGEMENTS

W. Reyenga and J. Galbraith collected data sets across the study sites. Prof. P. Schwerdtfeger and Dr J. Hacker (Flinders Univ., SA.) facilitated the Mallee study. CSIRO colleagues, Drs C. Smith, H. Cleugh, and P. Ward exchanged data to demonstrate the strength of the Priestley-Taylor formulation for characterization while Drs O. T. Denmead and R. Leuning furnished data sets on soil evaporation to impress on us the importance of soil evaporation in characterization.

7. REFERENCES

Battaglia, M. and P. Sands, Modelling site productivity of Eucalyptus globulus in response to climatic and site factors, *Australian Journal of Plant Physiology* 24, 831-850, 1997.

Denmead. O. T., Dunin, F. X., Leuning, R., and M. R. Raupach, Measuring and modelling soil evaporation in wheat crops, Special Issue of Physics and Chemistry of the Earth, European Geophysical Society, pp2-5.

Dunin, F. X., J. Williams, K. Verburg and B. Keating, Can agricultural management emulate natural ecosystems in recharge control in south eastern Australia? *Agroforestry Systems*, 45, 343-364, 1999.

Dunin, F. X. and A. R. Aston, The development and proving of models of large scale evapotranspiration: an Australian study, *Agricultural Water Management*, 6, 305-323, 1984.

Hatton, T., P. Reece, P. Taylor, and K. McEwan, Does leaf efficiency vary among eucalypts in water-limited environments? *Tree Physiology*, 18, 529-536, 1998.

Priestley, C. H. B., and R. J. Taylor, On the assessment of surface heat flux and evaporation using large scale parameters, *Monthly Weather Reviews, 100*, 81-91, 1972.

Ritchie, J. T., Water dynamics in the soil-plant-atmosphere system, *Plant and Soil*, 58, 81-96, 1981.

Specht, R. L., Water use by perennial evergreen communities in Australia and Papua New Guinea, *Australian Journal of Botany*, 20, 273-299. 1972.

Ward, P.R., and F.X. Dunin, Growing season evapotranspiration from duplex soils in south-western Australia, *Agricultural Water Management 50*(2), 141-159, 2001.

White, D. A., F. X. Dunin, N. C. Turner, B. H. Ward, and J.H Galbraith, Water use by tree belts comprised of eucalyptus species, *Agricultural Water Management*, (in press), 2001.