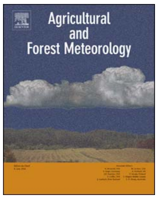
Agricultural and Forest Meteorology 248 (2018) 348–360

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Subsurface water-use strategies and physiological responses of subtropical eucalypt woodland vegetation under changing water-availability conditions

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ARTICLE INFO

Keywords:
Groundwater-dependent vegetation
Land surface temperature
Vegetation response
Drought

ABSTRACT

This study investigated subsurface water-use strategies and physiological responses of subtropical remnant eucalypt woodlands in south-eastern Queensland, Australia. A land surface temperature (LST) model-data approach was used to detect daily use of subsurface water (i.e. soil moisture obtained from depths > 30 cm and aquifer groundwater) by woody vegetation to a confidence level of 95%. Vegetation subsurface water use was quantified over a 13-year period (2000–2012) coinciding with a series of wet and dry climatic periods. Land surface temperature and subsurface water use time-series data were compared to local meteorological (vapour pressure deficit, rainfall, and soil water availability) and vegetation (leaf area index, stomatal resistance and latent heat loss) data to determine vegetation strategies to declining shallow (< 30 cm depth) soil water availability. Different vegetation subsurface water-use strategies and physiological response to changes in water availability were identified at inter- and intra-annual time-scales. At the intra-annual scale, frequency of subsurface water use by vegetation was strongly influenced by availability of shallow soil water. From January–September in this landscape, frequency of subsurface water use by vegetation remained relatively constant, supplementing decreasing shallow soil water availability and/or increasing evaporative demand. From October–December, the vegetation opportunistically utilised more abundant shallow soil water arising from more frequent, intense rainfall events, rather than relying on subsurface water. At the inter-annual scale, vegetation increased frequency of subsurface water use and decreased leaf area to reduce latent heat loss in response to dry conditions. Then, during wet years, subsurface water use by vegetation decreased in frequency as water was increasingly sourced from shallow soil layers. However, despite preceding dry periods of different severity, and exhibiting different average annual rainfall, air temperatures and reduction in the frequency of subsurface water use by vegetation, leaf area increased by approximately the same amount for both 'recovery' years. This suggests that investment in canopy leaf growth by this vegetation was more sensitive to the onset of increased water availability after drought rather than the overall volume of water made available by rainfall.

1. Introduction

Vegetation employ a range of water-stress avoidance mechanisms to maintain function and minimise water loss under water-deficit conditions including stomatal regulation over the short-term and decreased leaf area over the long-term (Carter and White, 2009; Chaves et al., 2003; Groom et al., 2001; Rood and Heinze-Milne, 1989; Smith et al., 1991; Whitehead and Beadle, 2004). Root depth distribution, morphology and functional plasticity in water uptake as a function of depth also enables vegetation to maintain the rate of water uptake under dry conditions by accessing water resources at increasing depths (Nippert and Holdo, 2015). *Eucalyptus* species across a range of climatic regions in Australia develop dimorphic root systems (i.e. lateral and deep tap roots; Canadell et al., 1996; Dawson and Pate, 1996; Sun and Dickinson, 1995) and have been found to supplement declining shallow soil water use with deeper subsurface water reserves during dry seasons or periods (e.g. Dawson and Pate, 1996; Farrington et al., 1996; O'Grady et al., 2006a; O'Grady et al., 2006b). Subtropical savanna studies have also found that, as shallow soil water resources declined, trees used proportionally more deeper soil water and groundwater resources as the proportion of roots in the shallow soil layer with access to soil water reduces (Kulmatiski et al., 2010; Kulmatiski and Beard, 2013; Nippert

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http://dx.doi.org/10.1016/j.agrformet.2017.10.005
Received 20 November 2016; Received in revised form 2 October 2017; Accepted 3 October 2017
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and Knapp, 2007).

Understanding vegetation water-use dynamics and physiological response to changes in water availability provide information about ecological water requirements and are thus important from environmental and water management perspective (Eamus et al., 2006; Eamus and Froend, 2006). Until recently, remote-sensing methods have been unable to quantify vegetation water-use dynamics (i.e. timing frequency, duration, and magnitude; Eamus et al., 2015). A novel land surface temperature (LST) model-data differencing approach (described in Gow et al., 2016a) detects subsurface water use (distinct from shallow soil water in the top 30 cm) by vegetation daily within 95% confidence intervals, at a regional-scale. With the development of the LST model-data differencing approach, frequency and timing of subsurface water use by vegetation can now be related to inter- and intra-annual climatic variation and vegetation structural and/or functional change.

Using the LST model-data differencing approach, this study aimed to identify responses in leaf area and stomatal resistance and subsurface water-use strategies employed by vegetation in a subtropical mixed woodland/agricultural study area under different water-availability conditions through time-series analysis. This paper describes: (1) the principles of LST as an indicator of water use by vegetation, (2) the LST model-data differencing approach and modifications made to the approach in this study, (3) methods used to convert daily climate, vegetation and LST data into weekly time-series composites, and compare frequency of subsurface water use by vegetation (ssw_{use}) with vegetation physiological characteristics (vegetation latent heat loss, stomatal resistance and leaf area index), and climatic conditions (rainfall, vapour pressure deficit and soil water availability). It then describes the combination of mechanisms (i.e. transient dependence on shallow soil water and subsurface water, control on leaf area and stomatal resistance) used by woodland vegetation in the study area in response to natural variation in water availability at intra- and inter-annual timescales.

2. Methodology

2.1. Land surface temperature as an indicator of water use

In response to climatic conditions, plants use stomata to regulate water loss via transpiration which in turn, along with humidity, temperature, wind speed and radiation, control surface temperature of the leaves (Anderson et al., 2011; Zarco-Tejada et al., 2013). As evapotranspiration (ET) and LST are responsive to varying micrometeorological conditions, remotely-sensed estimates of ET and LST can be used as indicators of water use by vegetation on daily to sub-daily temporal scales (Anderson et al., 2011; Friedl, 2002; Glenn et al., 2007; Guerschman et al., 2009; Moran, 2003; Zarco-Tejada et al., 2013). Satellite-derived LST data are often used to derive ET estimates (see review by Kalma et al., 2008) and as such these ET estimates are subject to uncertainty arising from conceptualisation of physical processes of latent heat flux and ET model equations (Overgaard et al., 2006). Thus less uncertainty arises from direct use of LST.

Land surface temperature is the physical (skin, radiometric) temperature of the surface and is an integral of component temperatures (e.g. leaves, trunks, branches, and ground). All other factors being equal (e.g. wind speed, vapour pressure deficit, air temperature and canopy conductance), ecosystems with access to plant-available subsurface water will have a lower LST (and higher ET) than ecosystems that do not. Land surface temperature can be independently modelled (e.g. Friedl, 1995, Friedl, 2002) and retrieved from remotely-sensed thermal data (e.g. Coll et al., 2010; Jiménez-Muñoz et al., 2009; Jiménez-Muñoz and Sobrino, 2003; Li et al., 2004; Qin et al., 2001; Sobrino et al., 1996; Wan and Dozier, 1996).

2.2. Model-data differencing approach

The LST model-data differencing approach described by Gow et al. (2016a, b) detects subsurface water use by vegetation in space and time within 95% confidence intervals, through differences in modelled LST ($T_{s.mod}$) and satellite observations of LST ($T_{s.obs}$) after accounting for random and systematic error in the model and data. Satellite observations of LST are an instantaneous measure of the area-weighted average surface thermal radiance in each pixel within the satellite-borne sensor field-of-view at the time of overpass (Wan et al., 2004), and captures water use from all available sources. Satellite observations of LST used in the model-data approach were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra satellite (MOD11A1; LP DAAC, 2014a). The Terra satellite has a sun-synchronous daily orbit, providing daily imaging of morning (~10:30am local time) LST. Morning LST is less prone to cloud cover (Anderson et al., 1997; Wetzel et al., 1984) and coincides with increasing or peak stomatal conductance and transpiration (Olioso et al., 1996; Tuzet et al., 2003). Terra-MODIS thermal infrared imagery has 1-km spatial resolution and a reported standard (random) error of ± 1 K (Coll et al., 2009; Wan, 2008; Wan and Li, 2008), although atmospheric effects and/or uncertainty in emissivity estimation can produce larger standard error (Hulley and Hook, 2009; Wan, 2008; Wan and Li, 2008).

Modelled LST was derived using a two-layer surface energy balance (SEB) model (see Friedl, 1995, 2002) which is driven by soil water content, net radiation and meteorological (air temperature, vapour pressure, wind speed) forcing data. The model comprises six equations solved simultaneously for three temperature (soil, vegetation and at the effective height of heat exchange) and three vapour pressure variables (soil, vegetation and at the effective height of heat exchange). The solutions were then used to calculate sensible and latent heat fluxes, and $T_{s.mod}$. The full suite of model equations are provided in Gow et al. (2016b). The SEB model was resolved at 250 m (averaged to 1-km resolution coincident with $T_{s.obs}$ data) and as it is driven by soil water content in the top 30 cm only, $T_{s.mod}$ represents water use from shallow soil water (i.e. surface water and soil water in the top 30 cm of the soil profile). As $T_{s.mod}$ represents LST arising from shallow soil water use and $T_{s.obs}$ represents LST arising from all water sources, the temperature difference (ΔT_s) between $T_{s.mod}$ and $T_{s.obs}$ captures both the subsurface water-use signal (i.e. all water below 30 cm depth) and error.

The model-data approach estimates and removes systematic error to yield vegetation subsurface water use, while consideration of random errors allows confidence intervals to be defined in association with subsurface water use (see Gow et al., 2016a). Systematic error or bias, is estimated from ΔT_s values for grassland vegetation based on an assumption that these vegetation communities do not access subsurface water under certain climatic conditions. Therefore $T_{s.mod}$ should equal $T_{s.obs}$. Random error in $T_{s.obs}$ was estimated from the literature, with the upper estimate (3.4 K) chosen to represent a conservative estimate of random error (Gow et al., 2016a). Random error in $T_{s.mod}$ was quantified using a sensitivity and uncertainty analysis described by Gow et al. (2016a), parameter sensitivities estimated using the Jacobian method, error variances obtained from literature and random error quantified using a Taylor's series error approximation.

2.2.1. Modification to LST model-data difference approach

Previous applications of the SEB model in the model-data approach (see Gow et al., 2016a,b) used shortwave radiation data (S_d; W m^{-2}) derived from visible-band satellite imagery processed for the Australian Water Availability Project (AWAP) by the Bureau of Meteorology (see Jones et al., 2006) from the Geostationary Meteorological Satellite series. Examination of this instantaneous AWAP S_d dataset revealed potential underestimation, with near zero shortwave radiation observed on occasion. Comparison was made between AWAP S_d and an independently derived reanalysis S_d dataset produced by the Centre for Ocean-Land Atmosphere Studies from the National Centres for

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