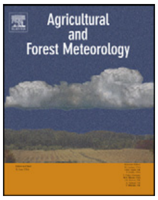
Agricultural and Forest Meteorology 157 (2012) 77–85

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

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



Dynamics of evapotranspiration partitioning in a semi-arid forest as affected by temporal rainfall patterns

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ARTICLE INFO

Article history:
Received 1 August 2011
Received in revised form
26 December 2011
Accepted 21 January 2012

Keywords:
Evapotranspiration partitioning
Tree transpiration
Soil evaporation
Temporal precipitation pattern
Semi-arid
Pine forest
Soil water adsorption

ABSTRACT

We extend our recent study of the effects of tree density on evapotranspiration (ET) partitioning in a semi-arid pine forest by examining the influence of the temporal patterns in rainfall (P) on the dynamic contributions of tree transpiration (T_t), soil evaporation (E_s) and rainfall interception (I_P) to total ET. Soil evaporation accounted for 39% of average annual ET over the four-year period, and was associated with soil moisture content in the upper 5 cm and solar radiation, therefore peaking during the wetting and drying seasons (up to 0.75 mm day^{-1}). In the dry summer, E_s diminished and as much as 50% of the residual flux was due to re-evaporation of moisture condensed at night (adsorption). Tree transpiration accounted for 49% of average annual ET, and was associated with soil moisture at a depth of 10–20 cm. Transpiration peaked only in late spring (1.5 mm day^{-1}), after the accumulation of large storms allowing infiltration below the topsoil. Moisture at these depths was maintained for longer periods and was even carried over between rain seasons following a high precipitation year. Interception was 12% of annual ET but was larger than 20% during the rainy period. The results indicated that both T_t/ET and E_s/ET could vary between 30% and 60% due to their differential response to seasonal environmental drivers. Annual T_t/ET, a major parameter indicating forest productivity and survival, was more influenced by the occurrence of large storms (>30 mm; P_{30}/P ratio) than by P itself. In an assessment of the potential warming and drying trends predicted for the Mediterranean region in the next century, changes in both total precipitation and in its temporal patterns must be considered.

1. Introduction

Evapotranspiration (ET) is an integrated term, composed of the linked vapor fluxes of plant transpiration (T), soil evaporation (E_s) and canopy-intercepted precipitation (I_P). Whereas E_s is a physically controlled flux, T is strongly influenced by plant physiology and can be affected by abiotic environmental conditions, but also by plant species characteristics, stomatal sensitivity, mycorrhizal associations, plant disease, atmospheric CO_2 concentrations and nutrients. A growing awareness of the importance of ecohydrology has motivated efforts to partition ET into its components, as a key to unraveling processes underlying ecosystem water use and its response to change (Huxman et al., 2005). Previous studies show that the T/ET ratio varies greatly among ecosystems and timescales, but on an annual basis it is mostly in the range 40–70% (Reynolds et al., 2000; Mitchell et al., 2009; Moran et al., 2009; Zhongmin et al., 2009; Cavanaugh et al., 2010; Staudt et al., 2011). This range of ratios emphasizes that even in water-limited environments, plants do not use all of the precipitation input and major water losses occur, mainly to E_s and runoff. Vegetation type, through its effect on the proportion of the shaded surface fraction, also influences T/ET, which generally increases from grasses to shrubs to trees (Kostner, 2001; Moran et al., 2009; Raz-Yaseef et al., 2010a; Wang et al., 2010). The T/ET ratio has been shown to vary among ecosystems according to the depth of water uptake, and is larger for deep-rooted trees than for grasses, as well as for soils with better infiltration regimes than more impermeable soils (Scholes and Archer, 1997; Laio et al., 2001; Kurc and Small, 2004; Cavanaugh et al., 2010).

When precipitation is characterized by short and sporadic showers, such as observed in some semi-arid sites (e.g. Sharon, 1972; Sala and Lauenroth, 1982; Lapitan and Parton, 1996; Loik et al., 2004), infiltration depth can be reduced, limiting moisture to shallow depths. Soils with high densities and fine textures exhibit low infiltration rates and high water holding capacities, further constraining infiltration (e.g. Noy-Meir, 1973; Reynolds et al., 2000; Scott et al., 2000; Kochendorfer and Ramírez, 2008). Even in such

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0168-1923/$ – see front matter
doi:10.1016/j.agrformet.2012.01.015

cases, infiltration below the topsoil can occur following infrequent events with relatively large rain amounts. In some extreme events, deep infiltration can lead to soil moisture "storage" through the dry season and into the following wet seasons, as has been reported in dry ecosystems (Paruelo et al., 2000; Kurpius et al., 2003; Tietjen et al., 2009; Raz-Yaseef et al., 2010b). Pulsed precipitation events that lead to infiltration deep enough to increase root uptake have a marked effect on above-ground biomass production (Schwinning and Sala, 2004; Heisler-White et al., 2008; Knapp et al., 2008) and can contribute to ecosystem resilience and survival under drought conditions.

Quantifying T/ET is key to predicting ecosystem survival and productivity, especially in water-limited regions. This is extremely important in light of the drying and warming trends predicted for the entire Mediterranean region and the southwestern US (IPCC, 2007). The objective of this four-year study was first, to define the dynamics of ET partitioning on seasonal and, within limits of the data-collection period, annual time scales. Second, we aimed to identify the main environmental and meteorological conditions affecting this flux partitioning. Finally, we attempted to connect ET partitioning to the large observed variations in temporal precipitation patterns in the semi-arid pine forest ecosystem.

2. Methods

2.1. Study area

Yatir Forest is located in Southern Israel, at the transition zone between sub-humid Mediterranean and arid climates, on the edge of the Judean Mountain ridge (31°21′N and 35°02′E, 630 m AMSL). The site is a ca. 45-year-old *Pinus halepensis* afforestation, currently spread over an area of 28 km^2, with a density of ~300 trees ha^{-1}, leaf area index (LAI) of ~1.50 $m^2\ m^{-2}$, and sparse understory vegetation (Maseyk et al., 2008; Grunzweig et al., 2009; Rotenberg and Yakir, 2010; Sprintsin et al., 2011). Average air temperatures for this region are 10 and 25 °C for the coldest and hottest months, January and July, respectively. Average precipitation for the last 30 years is 285 ± 88 mm $year^{-1}$. Nearly all precipitation falls between December and March, followed by an extended dry period during the hot summer. Potential ET (1600 mm $year^{-1}$) largely exceeds precipitation inputs. The soil at the research site is shallow (20–40 cm), Aeolian-origin loess with a clay-loam texture (0.31 ± 0.02 sand, 0.41 ± 0.10 silt and 0.28 ± 0.04 clay; density: 1.65 ± 0.14 g cm^{-3}) overlying chalk and limestone bedrock. Deeper soils (up to 1.5 m) are sporadically located at topographic hollows. While the natural rocky hillslopes of the semi-arid northern Negev are known to produce flash floods, the forest reduces runoff dramatically (to less than 5% of precipitation, Shachnovich et al., 2008). Groundwater is deep (>300 m), eliminating the possibility of groundwater recharge or utilization.

2.2. Meteorological measurements

An instrumented tower was erected in the geographical center of Yatir forest, following Euroflux methodology (Aubinet et al., 2000). The system uses a 3D sonic anemometer (Omnidirectional R3, Gill Instruments) and a closed path LI-COR 7000 CO_2/H_2O gas analyzer (LI-COR Inc.) to measure the evapotranspiration flux (ET) and net CO_2 flux (NEE). The flux tower's footprint was defined according to Gockede et al. (2008), indicating that the largest contribution to the flux during the day was from an area 34 m away from the tower and that 95% of the recorded flux came from an area within 1300 m of the tower. Wind direction was from the northwest to southwest sector during 64% of the day.

Air temperature ($Temp_a$) was measured with temperature probes at heights of 1, 5, 9, 15 and 19 m. Soil temperatures ($Temp_s$) at 2 and 6 cm depth were measured at six different points around the tower with thermocouples. Wind speed (W_S), wind direction (W_D), relative humidity of the atmosphere (RH), shortwave radiation, longwave radiation and photosynthetically active radiation were measured above and below the canopy, at heights of 15 and 1 m, respectively; both the upward and downward components of radiation were measured (Rotenberg and Yakir, 2011).

Precipitation (P) was measured by (1) a recording rain gauge (Campbell Scientific, USA) positioned at a height of 15 m on top of the flux tower, collecting data every half hour, and (2) a standard rain station positioned in a clearing in the forest, at a distance of 1.50 km from the tower site, from which data have been manually collected on rainy days since 1971. Data from this rain station (Yatir forest, KKL) were used to determine long-term average annual precipitation for the site. Data from the rain gauge were used to calculate intercepted precipitation (I_P) for individual rain events, based on the equation provided by Shachnovich et al. (2008):

$$I_{P(\mathrm{mm})} = P\ (\mathrm{mm}) - 0.94 \cdot P(\mathrm{mm}) - 0.76 \qquad (1)$$

2.3. Soil water content

Volumetric soil water content (θ) was measured at a half-hour time resolution with three reflectrometry sensors (CS616, Campbell Scientific) positioned vertically in the ground and measuring an average value for soil depth of 0–30 cm (θ_{0-30}). A specific calibration equation was prepared in the laboratory for these sensors to fit the dense soil at our site (according to the manufacturer's instructions). The sensitivity of the CS616 measurements to temperature was corrected by the factory-defined temperature-correction equation. Soil temperatures were measured at depths of 1, 5, 15 and 30 cm in close proximity to the CS616 sensors (HOBO H8 loggers, Onset Computers). In 2005, time domain reflectometry (TDR) sensors (TRIME, IMKO Inc.) were installed horizontally in three different pits dug around the tower. The pits varied in depth according to the soil/bedrock structure at each site. Sensors were installed horizontally, at constant depths of 5, 15, 30 (deepest sensor in pit 1), 50, 70 (deepest sensor in pit 2) and 125 cm (deepest sensor in pit 3). Variability between sensors of similar depths but different positions (pits) was less than 5%. Values of θ_x (x = 5, 15, 30, 50, 70 or 125 cm) presented herein are averages of the one to three sensors available for a particular depth. These values denote soil moisture measured at a specific depth, rather than the integral measurement of the previous method (CS616) for depth 0–30 cm (θ_{0-30}).

2.4. Transpiration

Sap flux was used to estimate tree transpiration (T_t; the subscript 't' is added to emphasize that while there is an additional, very small below-canopy component, here only tree transpiration is considered) with two similar techniques: the 'T_{max}' heat-pulse velocity method (HPV; Cohen, 1994) and the Granier method (Granier, 1987). HPV temperature signals were converted to mass flow rate based on empirical calibration coefficients suitable for Yatir trees (type and size; Schiller and Cohen, 1998; Cohen et al., 2008). The HPV system was operated during 2003/2004 and 2004/2005; the Granier system was operated during 2005/2006. Measurements were conducted hourly (including night hours) for eight trees representing average forest tree size, age and slope aspect in the flux-tower footprint. Water uptake ($L\ h^{-1}\ tree^{-1}$) was converted to T_t ($mm\ h^{-1}$) according to forest tree density (300 ha^{-1}). The Granier sensors were shorter than the HPV sensors (20 and 60 mm, respectively) and did not reach all depths of the conductive sapwood. According to Cohen et al. (2008), conductive sapwood diameter for semi-arid *Pinus halepensis* is ~40 mm, but sap velocity decreases with diameter. According to these findings,