Agricultural Water Management 177 (2016) 359–368

Contents lists available at ScienceDirect

Agricultural Water Management

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

Estimating water use of mature pecan orchards: A six stage crop growth curve approach

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ARTICLE INFO

Article history:
Received 15 June 2016
Received in revised form 20 August 2016
Accepted 22 August 2016
Available online 30 August 2016

Keywords:
Evapotranspiration
Crop coefficients
Growing degree days
Fractional canopy cover
Perennial

ABSTRACT

Mature pecans use large quantities of water and therefore the accurate estimation of water use or evapotranspiration (ET) of pecan orchards is critical for judicious irrigation water management and planning. Measuring ET under all possible combinations of climate and management practices is not possible, and as a result, models are used to estimate ET. Empirical modelling approaches are more widely adopted than the more complex mechanistic models, as they are more easily parameterized, but they are not always easily transferred across a wide range of growing conditions, making local evaluation and validation essential. This study evaluated existing crop coefficient models in a mature pecan orchard for three seasons in a semi-arid subtropical climate. Whilst the generic FAO-56 approach, using parameters provided for stone fruit performed reasonably well on a seasonal basis, accurate monthly estimates of ET were not achieved throughout the season. A closer analysis of data from the current study and a previous study in New Mexico, revealed that a six stage crop coefficient curve should be considered for pecans, together with higher mid-season crop coefficient (K_c) values for mature orchards. More accurate estimates of monthly ET for mature pecan orchards were obtained when reference K_c ($K_{c\text{-ref}}$) values for a well-managed mature pecan orchard in New Mexico were adjusted for local conditions of climate, using a growing degree day—K_c relationship and canopy cover. The adjustment for climate should, however, be used with caution. A comparison between seasons at Cullinan and with New Mexico suggests that whilst thermal time is likely to predict the start of leaf fall, it is unlikely to accurately predict canopy development at the start of the season. As a result it is suggested that in future a crop growth curve based on visual observations of phenological stages is developed.

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1. Introduction

Adequate water supply is crucial for optimal fruit production, with the consequence that the vast majority of orchards are dependent on irrigation, particularly in arid and semi-arid climates where rainfall is low and erratic. Consequently, irrigation water management and planning become vital factors for maximization of orchard profitability. This is particularly true for pecans as they require large amounts of water, relative to other crops, for adequate production, with water stress during the season reducing both yield and quality of the nuts (Garrot et al., 1993). Pecans are also often grown in water scarce regions (Wang et al., 2007), as the incidence of pecan scab is low in these dry climates and there is sufficient heat to mature the crop.

Although pecans are an important crop in a number of countries, such as the United States of America, Mexico, South Africa and Australia (INC, 2011), the majority of pecan research has been conducted in the USA. Studies conducted in New Mexico report that seasonal crop evapotranspiration (ET) of mature, flood-irrigated pecan orchards varies between 1095 and 1307 mm (Miyamoto, 1983; Sammis et al., 2004; Samani et al., 2009). The large variation in reported ET for mature pecans is mostly attributed to differences in tree spacing and pruning strategies, which result in variations in fractional canopy cover (fraction of ground covered or shaded by the vegetation) (Wang et al., 2007). Additional factors affecting ET include cultivar, soil type, irrigation system characteristics, climate and the presence of a cover crop or mulch on the soil surface (Pereira et al., 2015). Field trials to quantify ET of pecan orchards under

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http://dx.doi.org/10.1016/j.agwat.2016.08.024
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such a wide range of conditions are costly, time consuming and impractical. Crop models have therefore been used extensively to extrapolate information gathered from field studies to orchards in different climatic zones and under different management regimes, in order to aid growers with irrigation management. It was as a result of the need for more definitive knowledge on orchard water use that the Water Research Commission of South Africa solicited and funded a project on measurement and modelling of orchard water use, which included pecan, with co-funding from the South African Department of Agriculture, Forestry and Fisheries (Gush and Taylor, 2014).

There are a number of generic and specific crop models for estimating pecan water use, which vary in complexity and detail (Miyamoto, 1983; Allen et al., 1998; Annandale et al., 1999; Andales et al., 2006; Wang et al., 2007; Samani et al., 2011; Sammis et al., 2013). Complex, detailed models may be more explanatory and more accurately transferred to different situations, but they usually require a number of inputs which may not be practical or easy to obtain in field situations (Annandale et al., 1999; Andales et al., 2006). Simple crop models, on the other hand, are usually more empirical, based on robust relationships between plant behaviour and key environmental variables, but only tend to apply within their calibration range. They therefore do not always apply outside the area in which the relationships were developed. However, due to their limited input requirements, they are often more easily adopted by farmers. The FAO-56 model (Allen et al., 1998) and the pecan monthly water use simulator (Samani et al., 2011) are two such models, in which crop ET is calculated from meteorological data and single crop coefficients (K_c).

The major limitation of using empirical approaches to water use of orchards is that crop coefficients vary between orchards, with midseason K_c values for mature pecan orchards of between 1.1 and 1.39 reported in the arid New Mexico climate (Miyamoto, 1983; Sammis et al., 2004). Various modelling approaches, both generic and pecan-specific, have been developed to adjust crop coefficients to specific climatic conditions and orchard management practices using weather variables, thermal time, crop height, fractional canopy cover and the degree of stomatal control on crop water use (Miyamoto, 1983; Allen et al., 1998; Sammis et al., 2004; Wang et al., 2007; Allen and Pereira, 2009; Samani et al., 2011; Taylor et al., 2015). Whilst FAO-56 provides a simple, generic procedure for adjusting K_c values for climate using wind speed, minimum relative humidity and crop height (Allen et al., 1998), pecan-specific water use models have focused on adjusting K_c values of pecans according to fractional canopy cover and thermal time (Wang et al., 2007; Samani et al., 2011). Similar simple relationships between K_c and fractional canopy cover (estimated as fraction of midday radiation intercepted by the canopy) have been established for other deciduous crops, including peaches and grapes (Johnson et al., 2000; Snyder et al., 2000; Johnson et al., 2002; Williams and Ayars, 2005; Goodwin et al., 2006; Marsal et al., 2014). Unfortunately, these empirical modelling approaches are seldom evaluated in production regions other than where they were developed, which differ in both climate and irrigation system employed. Thus, they often contain artefacts of the local growing conditions, making them less transferable to areas with very different conditions, with consequent impacts on irrigation water management and planning.

Therefore, this study aimed to evaluate the transferability of simple single crop coefficient modelling approaches to estimate monthly ET of mature pecan orchards. The variability in ET caused by irrigation system characteristics and evaporation, as a result of the absence or presence of cover crops, was expected to be minimal in mature pecans orchards, where the ground is mostly shaded by the very large trees. As a result single crop coefficients are likely to capture climate driven changes in ET. In addition, it was expected that in mature orchards, differences in spacing and pruning practices could be accounted for by scaling crop coefficients according to the fractional canopy cover, as demonstrated in other fruit tree crops. As pecans are grown in a wide range of climates, where the rate of canopy development and leaf fall differ quite widely, it was also expected that thermal time would adequately explain these differences and allow the stretching and shrinking of the crop coefficient curve.

2. Materials and methods

2.1. Experimental sites

The experimental site was located within the summer rainfall area of South Africa at Cullinan in the Gauteng Province (25°35′20.65″S and 28°33′31.90″E; approximately 1340 masl). The climate of the study area is semi-arid subtropical, generally characterized by long, hot summers (from September to April) and short, cold winters (from May to August). Average annual rainfall is 673 mm, with daily mean temperatures varying between 9.7 and 21.2 °C (Schulze and Lynch, 2006; Schulze and Maharaj, 2006).

Field measurements were conducted in a mature, 22 ha commercial, mixed cultivar pecan orchard, planted in 1975. Measurements were conducted over three consecutive seasons from September 2009 until May 2012 in two 'Choctaw' pecan trees on 'Barton' rootstocks. Trees were arranged triangularly in a 9 m × 9 m × 9 m spacing, along a N-NE to S-SW axis. The orchard was irrigated using a single micro-sprinkler per tree, with a wetted diameter of 7 m and delivery rate of 90 L h^{-1}. Irrigation was typically scheduled once every six days for 24 h (equivalent to 31 mm) and was recorded using a logging in-line electrode and water meters, which were read every 2 weeks. This schedule was adjusted according to the amount of rainfall received. The average tree height was 13 m after pruning, with an average trunk diameter of 0.43 m, when measured 50 cm from the soil surface. Average yield during the study period (from 2009 to 2012) was 1.9 t ha^{-1} annum^{-1} in-shell, with an "off" season (2010/2011) yielding 1.3 t ha^{-1} and an "on" season yielding 2.2 t ha^{-1}. Pruning strategies varied throughout the three monitoring seasons, with the aim of achieving maximum sunlight penetration throughout the canopy. In the 2009/2010 season, light mechanized hedge pruning, manual selective limb pruning and top pruning were performed. In the 2010/2011 season, light mechanized hedge pruning and top pruning were employed, whilst in 2011/2012 heavy mechanized hedge pruning and top pruning were carried out. The soil type was sandy to sandy clay, with the clay content increasing down the soil profile (from 7 to 45%). Organic fertilization and zinc sulfate sprays were conducted following recommendations based on soil and leaf analyses.

2.2. Quantification of actual evapotranspiration of pecan orchards

Actual ET of pecans during the experimental period was estimated as the sum of transpiration (T), measured continuously with a calibrated heat ratio method, and soil evaporation (E_s) estimated with a successfully calibrated and validated FAO-56 soil evaporation model (Allen et al., 1998; Allen et al., 2005) using a window period of E_s measurements at the experimental site (Figs. 1 and 2).

2.3. Field measurements

2.3.1. Fractional interception of photosynthetically active radiation by the canopy

Fractional interception of photosynthetically active radiation (PAR) of six trees at the experimental site was measured every two weeks using a Decagon AccuPAR LP-80 ceptometer (Decagon

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