Agricultural Water Management 208 (2018) 152–162

Contents lists available at ScienceDirect

Agricultural Water Management

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

Estimating the water requirements of high yielding and young apple orchards in the winter rainfall areas of South Africa using a dual source evapotranspiration model

S. Dzikiti[a,*], T. Volschenk[b], S.J.E Midgley[c], E. Lötze[c], N.J Taylor[d], M.B. Gush[a], Z. Ntshidi[a], S.F Zirebwa[c], Q. Doko[d], M. Schmeisser[c], C. Jarmain[f], W.J Steyn[c,e], H.H. Pienaar[a]

[a] *Council for Scientific and Industrial Research (CSIR), Natural Resources and Environment, Stellenbosch, South Africa*
[b] *Agricultural Research Council (ARC), Infruitec-Nietvoorbij, Soil and Water Science Program, Stellenbosch, South Africa*
[c] *Department of Horticultural Science, University of Stellenbosch, South Africa*
[d] *Department of Plant and Soil Sciences, University of Pretoria, South Africa*
[e] *HORTGRO Science, South Africa*
[f] *University of Stellenbosch, South Africa*

ARTICLE INFO

Keywords:
Canopy cover
Orchard floor evaporation
Transpiration
Water use model

ABSTRACT

Exceptionally high yielding (> 100 t ha^{-1}) apple orchards (*Malus domestica* Borkh.) are becoming common in South Africa and elsewhere in the world. However, no accurate quantitative information currently exists on the water requirements of these orchards. Information is also sparse on the water use of young apple orchards. This paucity of data may cause inaccurate irrigation scheduling and water allocation decisions, leading to inefficient use of often limited water resources. The aim of this study was therefore to investigate the dynamics of water use in eight apple orchards in South Africa planted to Golden Delicious and the red cultivars i.e. Cripps' Pink, Cripps' Red and Rosy Glow in order to understand how canopy cover and crop load influence orchard water use. Four of the orchards were young (3–4 years after planting) and non-bearing, while the other four were mature high yielding orchards. Transpiration was monitored using sap flow sensors while orchard evapotranspiration (ET) was measured during selected periods using eddy covariance systems. Scaling up of ET to seasonal water use was done using a modified Shuttleworth and Wallace model that incorporated variable canopy and soil surface resistances. This model provided reasonable estimates in both mature and young orchards. The average yield in the two mature 'Cripps' Pink' was ~110 t ha^{-1} compared to ~88 t ha^{-1} in the 'Golden Delicious' orchards. However, average transpiration (Oct-Jun) was ~638 mm for the 'Cripps' Pink' and ~778 mm in the 'Golden Delicious' orchards. The peak leaf area index was ~2.6 and ~ 3.3 for the mature 'Cripps' Pink and 'Golden Delicious' orchards. So, canopy cover rather than crop load was the main driver of orchard water use. Transpiration by the young orchards ranged from 130 to 270 mm. The predicted seasonal total ET varied from ~900 to 1100 mm in the mature orchards and it was ~500 mm in the young orchards. Orchard floor evaporation accounted for ~18 to 36% of ET in mature orchards depending on canopy cover and this increased to more than 60% in young orchards.

1. Introduction

Irrigation is the single most repetitive operation in fruit production, especially in arid and semi-arid regions (Fernández and Cuevas, 2010; Liu et al., 2015). In key deciduous fruit exporting countries such as Spain, Italy and South Africa, most of the fruit is produced under irrigation (Consoli et al., 2016; Gush and Taylor, 2014). Therefore, the availability of adequate water is critical for the sustainability and growth of the fruit industries (Dzikiti et al., 2017a; Testi et al., 2006). Water resources in these countries are under severe strain from global climate change and increasing competition between different users (Midgley et al., 2014). The average yield of apple (*Malus domestica* Borkh.) orchards varies considerably between countries. In South Africa, for example, it is approximately 60 t ha^{-1} (Hortgro, 2016). However, in recent years, exceptionally high yielding orchards that consistently produce more than 100 t ha^{-1} have become common due to improved plant material and orchard management practices (W. Steyn, pers. comm.). This raises questions on the sustainability of these

* Corresponding author at: Natural Resources and the Environment, Council for Scientific and Industrial Research, 11 Jan Cilliers Street, 7599, Stellenbosch, South Africa.
E-mail address: sdzikiti@csir.co.za (S. Dzikiti).

https://doi.org/10.1016/j.agwat.2018.06.017
Received 28 March 2017; Received in revised form 15 April 2018; Accepted 13 June 2018

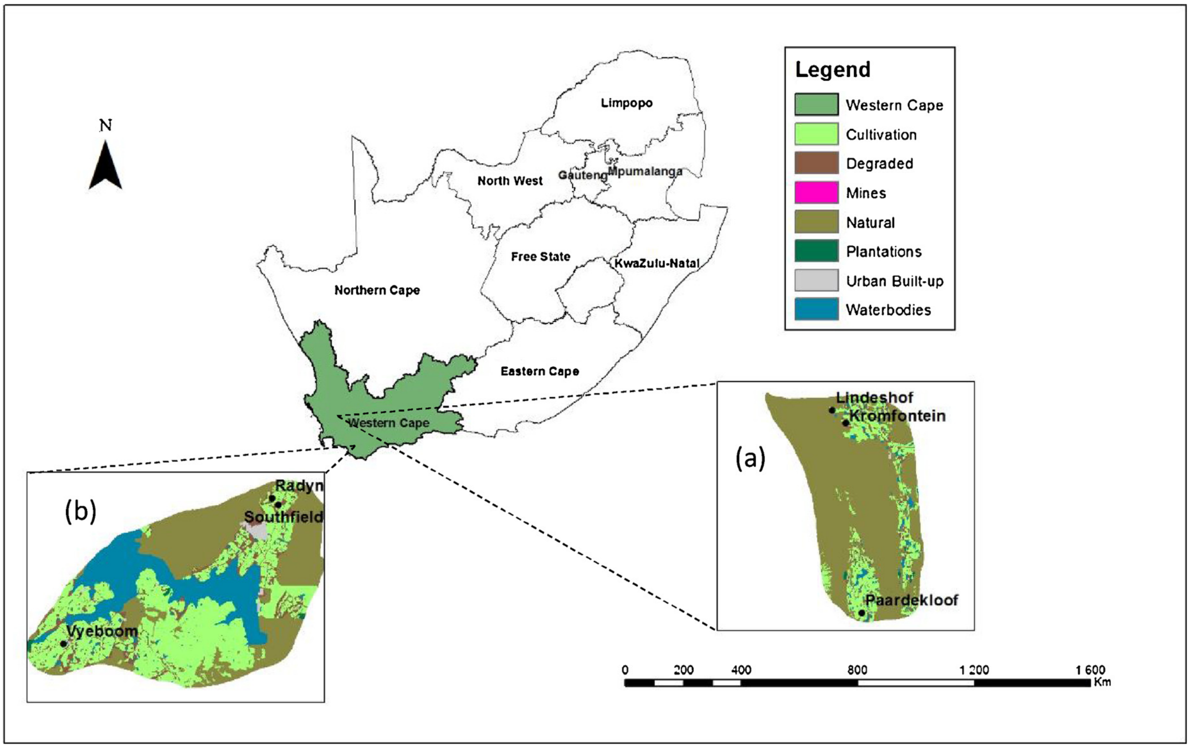

Fig. 1. Map of the two major apple producing regions in the Western Cape Province of South Africa namely the Koue Bokkeveld (KBV, insert a) and the Elgin/Grabouw/Vyeboom/Villiersdorp (EGVV, insert b).

orchards given the increasingly limited water resources since orchards with high yields of good quality fruit are reported to have higher water requirements (Naor et al., 1997, 2008). While many studies have quantified water use by apple orchards (Gush and Taylor, 2014; Volschenk et al., 2003; Volschenk, 2017), none of them have focused on exceptionally high yielding orchards.

A second important information gap relates to how water use by apple orchards varies from planting until the trees reach the full-bearing age (6–8 yr.). Some studies have quantified evapotranspiration (ET) and its partitioning into tree transpiration and orchard floor evaporation (Gong et al., 2007; Liu et al., 2015). However, these studies only investigated mature orchards and there is no detailed quantitative information on how ET and its components vary from planting until the trees mature. This information is important for irrigation scheduling, designing irrigation systems, water allocation, and developing strategies to cope with droughts, whose frequency and severity is projected to increase e.g. in the prime fruit producing Western Cape Province of South Africa (Midgley and Lötze, 2011).

Orchard evapotranspiration is commonly determined using the soil water balance approach (Rallo et al., 2017, 2014; Volschenk, 2017), micrometeorological techniques such as the eddy covariance (Gush and Taylor, 2014; Dzikiti et al., 2017a), combining micro-lysimeter derived soil evaporation and transpiration (Bonachela et al., 2001), and using the surface energy balance method (Cammalleri et al., 2010; Consoli and Papa, 2013; Consoli et al., 2005; Dzikiti et al., 2011). These methods are however, not suited for routine use in orchard water management. Instead, simple crop coefficients (K_c) are widely used to estimate ET from reference evapotranspiration (ET_o) ($ET = K_c \times ET_o$), using the guidelines provided in FAO paper number 56 (Allen et al., 1998). Whilst these have proven robust in a number of annual crops, they have been shown to be very site specific for perennial orchard crops where crop coefficients can vary according to variety, rootstock, tree spacing, canopy cover, microclimate and irrigation method (Naor et al., 2008). As a result, published K_c values can often result in poor estimates of water use for orchard crops. There is therefore a need for more mechanistic models which can provide reliable estimates of ET under a wide range of climatic conditions and management practices which can then be used to derive site specific K_c values for improved on-farm water resources management. However, in cases where the soil water content falls below threshold values, plants experience water stress and K_c can be adjusted for the stress according to:

$$ET = (K_{cb} \times K_s + K_e \times K_r)ET_o(mm\ d^{-1}) \quad (1)$$

where K_{cb} and K_e are the basal and soil evaporation coefficients, K_s and K_r are the transpiration and evaporation reduction coefficients described in detail by Allen et al. (1998) and Rallo et al. (2017).

According to Bastidas-Obando et al. (2017) and Kool et al. (2014), estimation of ET can be improved by modelling the transpiration and soil evaporation components separately since transpiration is disconnected from the soil physical conditions related to soil evaporation. The objectives of this study were to establish the water requirements of apple orchards with varying canopy cover and to quantify how orchard ET is partitioned into transpiration and orchard floor evaporation using the Shuttleworth and Wallace (1985) model. The novelty of this study resides in the fact that, we for the first time, quantify the water requirements of exceptionally high yielding apple orchards that consistently produce in excess of 100 t ha^{-1} and we document the key drivers of water use in order to inform orchard and water management decisions. Secondly, we provide quantitative information on the water use dynamics of young and mature orchards planted to apple cultivars commonly grown in the Mediterranean climatic regions namely the 'Golden Delicious' and the red varieties. Consoli et al. (2005) conducted a similar study in citrus orchards in Italy. However, there is no accurate information on how apple orchard water use varies from planting until the trees reach full-bearing age which is critical for developing accurate irrigation guidelines. Thirdly, we use this data to evaluate the performance of the modified Shuttleworth and Wallace model in a number of orchards in different climatic regions. The model can potentially be used to improve irrigation decision making e.g. by deriving accurate site-specific crop factors for orchards of different age groups.