



## Research Paper

# Low and variable atmospheric coupling in irrigated Almond (*Prunus dulcis*) canopies indicates a limited influence of stomata on orchard evapotranspiration



Gerardo M. Spinelli<sup>a,\*</sup>, Richard L. Snyder<sup>b</sup>, Blake L. Sanden<sup>c</sup>, Matthew Gilbert<sup>a</sup>, Ken A. Shackel<sup>a</sup>

<sup>a</sup> University of California, Davis, Dept. of Plant Sciences, One Shields Ave, Davis, CA 95616-8683, USA

<sup>b</sup> University of California, Davis, Dept. of Land, Air and Water Resources, One Shields Ave, Davis, CA 95616-8683, USA

<sup>c</sup> University of California Cooperative Extension, 1031 S. Mt. Vernon Ave., Bakersfield, CA 93307, USA

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## ABSTRACT

The degree of coupling to the environment of almond (*Prunus dulcis*) orchards during periods of transient water stress was investigated in a two-year study in California. Plant water status was monitored weekly, before and/or after irrigation, measuring midday stem water potential ( $\Psi_{\text{stem}}$ ) that ranged from  $-0.5$  to  $-2$  MPa, while actual evapotranspiration ( $ET_a$ ) was measured with an eddy covariance tower. Irrigation was applied weekly following common commercial practice, resulting in weekly cycles of  $\Psi_{\text{stem}}$ . Despite  $\Psi_{\text{stem}}$  reaching levels shown to induce substantial stomatal closure, the ratio actual to reference evapotranspiration ( $ET_a/ET_o = K_a$ ) did not show a decrease during weekly periods of low  $\Psi_{\text{stem}}$  in the two years of the study. Midday average canopy surface resistance ( $r_{\text{cmid}}$ ), computed by reversing the Penman-Monteith equation from eddy covariance ET data, yielded a statistically significant increase with a decrease in  $\Psi_{\text{stem}}$ , but just in the first year of the study. However,  $r_{\text{cmid}}$  did not show a significant relationship with stomatal resistance measured at the leaf level with porometry and scaled-up to the canopy level. In the first year,  $r_{\text{cmid}}$  showed a sharp increase after harvest, when  $K_a$  also decreased, perhaps produced by the composite effect of defoliation associated with harvest and stomatal closure associated with water stress. During the growing season,  $r_{\text{cmid}}$  ranged from 0 to  $100 \text{ s m}^{-1}$  and midday average aerodynamic resistance ( $r_{\text{amid}}$ ) ranged between 0 and  $50 \text{ s m}^{-1}$ . Despite  $r_{\text{cmid}}$  being generally larger than  $r_a$ , the midday average decoupling factor ( $\Omega$ ) averaged 0.7 during the irrigation season, indicating decoupled conditions. However, there was a large day to day fluctuation of midday  $\Omega$  ranging from 0.16 to 0.98 mostly associated with  $r_{\text{cmid}}$  and wind speed. This study indicated that tall and rough canopies can be relatively decoupled depending on the effect of wind speed and canopy resistance on the decoupling factor. From a water management point of view, this result suggests that inducing transient mild to moderate water stress may not produce substantial water savings in areas having low to moderate winds.

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## 1. Introduction

Almonds are the second largest crop of California by acreage with 328 thousand hectares (810 thousand acres) estimated in 2013, and produced a value of \$3.387 billion in 2012 (Almond Board of California). Essentially all commercial almond orchards are irrigated, making almonds the second largest crop of the State in terms of water use (California Department of Water Resources). Water stress occurs in commercial orchards as a result of water shortage, but short periods of water stress can also be induced as a management tool to control vegetative growth, reduce fungal diseases at hull split, and facilitate harvest operations. In a previous study (Spinelli, 2016) we showed that a substantial reduction (about

**Abbreviations:**  $C_p$ , air heat capacity at constant pressure;  $e_a$ , air vapor pressure;  $e_{s(T_a)}$ , saturated vapor pressure at air temperature;  $e_{s(T_s)}$ , saturated vapor pressure at surface temperature;  $ET_a$ , actual evapotranspiration;  $ET_o$ , reference evapotranspiration;  $G$ , ground heat flux;  $H$ , sensible heat flux;  $K_a$ , crop coefficient ratio of actual to reference ET; LAI, leaf area index;  $LE$ , latent heat flux;  $r_{\text{cmid}}$ , midday average canopy surface resistance;  $r_{\text{amid}}$ , midday average aerodynamic resistance;  $R_i$ , input radiation;  $R_n$ , net radiation;  $T_a$ , air temperature;  $u_z$ , wind speed at height  $z$ ;  $u^*$ , friction velocity;  $\gamma$ , psychrometric constant;  $\Delta$ , slope of the vapor pressure and temperature relation;  $\epsilon$ , surface emissivity;  $\rho$ , air density;  $\sigma$ , stefan-boltzmann constant;  $\Psi_{\text{stem}}$ , midday stem water potential;  $\Omega$ , midday average decoupling factor.

\* Corresponding author.

E-mail addresses: [gspinelli@ucdavis.edu](mailto:gspinelli@ucdavis.edu) (G.M. Spinelli), [rlsnyder@ucdavis.edu](mailto:rlsnyder@ucdavis.edu) (R.L. Snyder), [blsanden@ucdavis.edu](mailto:blsanden@ucdavis.edu) (B.L. Sanden), [megilbert@ucdavis.edu](mailto:megilbert@ucdavis.edu) (M. Gilbert), [kashackel@ucdavis.edu](mailto:kashackel@ucdavis.edu) (K.A. Shackel).

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50%) in both leaf-level photosynthetic rate and stomatal conductance occurs for the range of water status commonly observed in commercial orchards (from  $-0.5$  to  $-2$  MPa). Similar results were obtained by Klein et al. (2001) and Shackel (2011). Comparable reductions of stomatal conductance in association with water stress in almond trees have been shown using various measures of water availability such as the osmotic potential of a nutrient solution (Wartinger et al., 1990), predawn leaf water potential (Rouhi et al., 2007), and leaf water potential (Castel and Fereres, 1982). Photosynthetic rates ultimately determine biomass accumulation and indirectly yield, hence it can be argued that stomatal closure caused by periods of water stress may also reduce plant productivity. The question is whether transpiration is also reduced as a result of stomatal closure, and if irrigation water is saved. The answer to this question lies in the sensitivity of transpiration to stomatal closure in the context of an entire canopy.

Since transpiration is not only a function of stomatal conductance but also of the evaporative demand of the atmosphere, the effect of environmental factors needs to be taken into account. This is commonly achieved by calculating the actual crop coefficient ( $K_a$ ), the ratio of actual evapotranspiration ( $ET_a$ ) and reference evapotranspiration ( $ET_o$ ). The latter indicates the evapotranspiration of an unstressed grass field and hence is a composite measure of environmental factors. Two studies conducted on perennial crops planted in lysimeters (Johnson et al., 2005 in peach; Williams et al., 2012 in grapevines) have shown a reduction of the ratio  $ET_a/ET_o$  associated with a decreasing stem or leaf water potential as a result of stomatal closure. However the use of the ratio  $ET_a/ET_o$  is not devoid of problems, especially in the case of tall trees because a tall canopy responds to environmental variables (such as wind) differently to grass, and hence  $ET_o$  may not be the appropriate metric to make allowance for environmental variability (Annandale and Stockle, 1994).

A more appropriate way to separate physiological from environmental effects on  $ET_a$  for tall canopies may be to solve the Penman-Monteith “Big Leaf” model for canopy surface resistance<sup>1</sup> ( $r_c$ ) which is the variable under physiological control in the model and should show an increase associated with stomatal closure (Kelliher and Leuning, 1995; Baldocchi et al., 1991). Nevertheless, canopy resistance calculated using the Big Leaf model includes the effects of non-physiological variables (mostly aerodynamic) and is affected by soil surface wetness (Baldocchi et al., 1991; Paw U and Meyers, 1989; Kjølgaard and Stockle, 2001). Other studies have shown that at high leaf area indexes, canopy conductance is mostly a function of leaf area and it is not strongly affected by stomatal conductance (Steduto and Hsiao, 1998b).

The concept of coupling is an approach to describe the sensitivity of evapotranspiration to stomatal closure. Jarvis (1984) proposed a decoupling factor ( $\Omega$ ) that mathematically describes the relative change in evapotranspiration for a given relative change in  $r_c$  (Jones, 1992, Eq. 5.29). Coupling varies across scales, a leaf being more coupled to the environment than a single plant, and a plant being more coupled than a crop canopy (Jarvis and McNaughton, 1986). Plants evolved adaptations to survive as individuals in a much more coupled environment than a full crop canopy, which justifies the evolutionary effort of developing control mechanisms like stomatal regulation on transpiration. It may not be surprising that

<sup>1</sup> Different authors use resistance or conductance to express the degree to which a particular segment of the transport pathway produces a flux in presence of a gradient, but resistance and conductance are inversely related and their meaning is equivalent. In this study we will use resistances because in a canopy the physiological and aerodynamic segments of the transport pathway are in series and thus the total resistance is the sum of the individual resistances. In this case, the use of resistances is more informative about the relative contribution of each segment to the total transport path.

such mechanisms are not as effective in a decoupled crop canopy (Jarvis, 1985). However, even considering a single leaf, which is generally more coupled than a canopy, a large decrease in stomatal conductance may result in a marginal reduction in transpiration, depending on leaf boundary layer conditions (Bange, 1953). Forests, tree canopies and tall and rough vegetation are generally considered more coupled than grass or agricultural crops with short vegetation, since  $\Omega$  decreases with the relative importance of  $r_c$  with respect to  $r_a$ . In other words, a canopy gets more coupled as  $r_c$  increases (water stress) and as  $r_a$  decreases ( $r_a$  is always lower for a tall, rough canopy than for a short, smooth canopy and  $r_a$  decreases as wind speed increases). Rana and Katerji (1998) found that in tall sorghum canopies, ET depends strongly on  $r_c$ , especially when water stressed. Therefore, in theory, a water stressed almond canopy should be one of the most coupled agricultural crops.

The decoupling factor however, should not be considered a fixed characteristic of a canopy, because it is also dependent on wind speed, through its effect on  $r_a$ , and on air temperature, through the effect of temperature on  $\Delta$ , the slope of the relationship between vapor pressure and temperature (Monteith and Unsworth, 1990). For instance, Kostner et al. (1992) report a fourfold variation in the daily pattern of  $\Omega$  in a forest. Paw U and Gao (1988) showed that the omega factor, when derived from linear models, such as the  $\Omega$  proposed by Jarvis and McNaughton, can be in great error compared to quadratic or quartic solutions of the energy balance. They show considerable discrepancies of the result between the two models especially when  $\Omega > 0.8$  and when net radiation is considered constant as surface temperature increases.  $\Omega$  was also shown to be highly dependent on leaf area index (LAI) by Steduto and Hsiao (1998b). They found relatively high midday values of  $\Omega$  ranging from 0.4 to 0.8 in well watered and water stressed relatively tall (3 m) maize canopies. In that study, the observed high LAI was the major determinant of the large  $\Omega$ . Only when senescence caused a drop in LAI,  $\Omega$  decreased and canopy resistance began to exert a significant effect on transpiration. Most of the decrease in canopy resistance was attributable to a drop in LAI and only a minor component was due to stomatal closure.

The course of LAI in an almond orchard is different than in field crops. Almonds leaf out very rapidly starting from March with complete canopy closure occurring early, but vegetative growth continues until about the end of June. Thus, LAI is relatively constant during summer months and leaf senescence and abscission occurs in late Fall. However, partial defoliation is common in California almond orchards as they approach harvest (end of August) and leaf abscission is intensified by the mechanical stress of tree shaking during harvest. Klein et al. (2001) showed a close correlation between water stress and leaf abscission.

The objective of this study was investigating the following question: is orchard water use reduced with reductions in almond tree water status in the field? This question was developed into each step of the chain of processes leading stress-related stomatal closure to reduce ET, namely: a) to what degree is canopy resistance increased when water stress causes stomatal closure; b) what is the relative sensitivity ( $\Omega$ ) of evapotranspiration to canopy resistance; c) what environmental and physiological variables affect this sensitivity.

## 2. Materials and methods

### 2.1. Experimental site

The experiment was conducted in 2009 and 2010 in a high yielding almond (*Prunus dulcis* D.A. Webb) orchard at the Paramount Farming Company in Lost Hills, CA (N 35°30'37" W 119°40'3"). The plot was a rectangular irrigation set of the following dimen-

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