Modeling Hydraulic Dynamics at Different Levels of Fruit Tree Canopies under Abiotic Stress

E Kullaj[1]*, L Lepaja[1], V Avdiu[2] and F Thomaj[1]

[1]Department of Horticulture and Landscape Architecture, Agricultural University of Tirana, Albania

[2]Department of Fruit Trees and Viticulture, University of Pristina, Kosove

*Corresponding author: E Kullaj, Department of Horticulture and Landscape Architecture, Agricultural University of Tirana, Kodër-Kamëz, 1010, Albania.

Abstract

Tree canopy microclimate, influenced mainly by radiation, air temperature and wind affects both the vegetative and reproductive behaviour with a striking influence on both quantity and quality of production. The present study uses experimental data to model the xylem flows at various levels of canopy. The study was conducted on two commercial orchards with a central leader system from 2011 to 2012. Sap flow sensors based on SHB (stem heat balance) method were installed on shoots (10 - 12 mm) of five 8-years old trees of 'Golden Delicious' at different levels of the canopy (upper, middle, lower). Quantum sensors and infrared radiometers continuously measured PAR (photosynthetically active radiation) levels and canopy temperature at these three levels of the canopy. Stomata conductance was measured using a leaf porometer. A portable meteorological station measured meteorological variables enabling the calculation of VPD (vapour pressure deficit) and PET (potential evapotranspiration). Additionally, length, diameter TCSA (trunk cross-sectional area) and leaf area of shoots was measured too. The model was implemented in Mini32 software. A linear regression analysis was performed to study different regression models predicting the xylem flows based on measured environmental variables indicating which variable better predicts xylem flow at each canopy level. Results showed that xylem flows were better predicted by changes in ET (evapotranspiration) for the central and lower part of the canopy ($R^2 = 0.95$) while canopy temperature better predicted the flows of shoots at the upper part of the canopy ($R^2 = 0.90$).

Keywords: Canopy; Apple; Sap flow; Transpiration

Introduction

Fruit production provides an important contribution in the agricultural sector in Albania, providing about 20 percent of the total agriculture output. Apple is not only the main fruit produced in Albania, but its production has marked the highest growth by quadrupling between 1985 (18200 tons) and 2012 (71300 tons). Use of sap flow for either studying plant water relations or plant water use has received particular research and practical importance [1,2]. Various methods have been conceived attempting to increase the accuracy of measurement in a wide variety of species, organs and climatic or technological conditions.

Climatic variables like solar radiation (Rs), air temperature (Ta), canopy temperature (Tc), vapour pressure difference (VPD) and reference evapotranspiration (ET_0) drive or relate to sap flow. Solar radiation within the 400–700 nm wavebands (photosynthetic photon flux, PPF) drives the photosynthetic process, and global radiation (300–2500 nm waveband) provides the energy for transpiration activity [3]. The relationship is positive because increasing the radiation load on the leaf results in an increase in the dissipation of sensible heat and latent heat, even at constant levels of Ta and VPD [4-6]. Plant canopy geometry determines the spatial and temporal interaction between incoming radiation flux and foliage, and therefore plays a central role in quantifying the driving force for leaf physiological processes [7-10]. Effect of air temperature (and obviously canopy temperature) on SF is even higher and proportional. Varying levels of the latest influences relative humidity (RH) and consequently changes VPD altering the transpiration flow (and sap flow rates).

Most these variables change significantly within fruit tree canopies and depending on the level of canopy, their effect on sap flow could be different [11]. The purpose of the research presented here was to unravel the relationship between sap flow and the above (micro) meteorological variables at various levels of a tree canopy to demonstrate which of them better predicts sap flow and at what respective canopy level. Models that predict sap flow and therefore transpiration have important applications in many areas including agricultural production, automated irrigation, tree ecophysiology, climate change, hydrology, etc.

Material and Methods

Plant material

Eight–years old apple trees of cv. 'Golden Delicious' on a dwarfing M9 EMLA rootstock and trained according to a central leader system were used as replicates based on trunk diameter and other biometric measurements, i.e. affinity index, vigour, number of branches and shoots, etc. Homogeneity of these trees was evaluated under another study [12]. Trees were planted 3 × 1 m apart, in an N–S orientation, at a 6 ha commercial orchard in Lushnja (40°58'31.90"N 19°40'15.76" E). The plots were regularly irrigated until the measurement period. Trees were not pruned during the experiment, and crop load was adjusted by manual thinning in accordance with commercial practice. The division of tree canopies into three layers was based on their position relative to the main leader and their training in relation to the wires.

Discretization of the canopy

The division of tree canopies into layers was based mainly on light interception and canopy temperature. Light interception was characterized as silhouette to total area ratio (STAR) [13] using a modified 3-D mock up of an 8 – years old apple tree [14]. Canopy layer temperature was measured with an infrared radiometer (Apogee SI 100, www.apogeeinstruments.com). Using a combination of PAR values calculated from STAR and Tc, three classes or layer of canopy were defined, pertaining approximately to the division into upper, middle and lower canopy. Shadowing of adjacent rows and upper part of the canopy were the major factors determining the belonging of branches to the lower and medium layer.

Simplifications and codes chosen for multi scale descriptions of tree topology were used in previous studies [13,15-17]. On the basis of above canopy discretization, shoots about 12 mm thick belonging to each class of layer were labelled accordingly for SF measurement. Shoots chosen had an equal leaf area (LA). As the scope of this research was not to quantify the total SF but rather to predict it by meteorological variables, SF measured represent the average SF rate (kg/h) of 12 mm thick shoots belonging to a certain canopy layer but from different positions distances from the main leader as well as cardinal points.(*upper* = twigs coming out the bottom scaffold branches, at the level of the bottom wire support; *middle* = twigs coming out the middle primary branches at the level of the middle wire support; *lower* = twigs coming out from almost the top of the central leader, at the level of the third wire support).

Measurement of sap flow and (micro)meteorological variables

SF was measured using sap flow sensors EMS 62 (EMS Brno), based on SHB (stem heat balance) method [18,19]. Sensors were installed on shoots (12 mm thick) on 5 trees at three levels of the canopy. The measuring interval was every minute with 1 s warm-up and storing interval every 15 minutes during July

2012. Infrared radiometers (Apogee SI 100) continuously measured Tc respectively at these three canopy levels. A portable meteorological station Minikin RTHi (EMS Brno, CZ), located in the centre of the orchard, measured the Rs, Ta and RH. Calculation of VPD from relative humidity and PET (potential evapotranspiration) was implemented in Mini 32 (EMS Brno, CZ). The closest state meteorological station measured wind speed, rainfalls and ET_0.

Experimental design and statistical analysis

The design of the experiment was completely randomized with four replications, each replication consisting of three adjacent rows of five trees. Measurements were taken in the inner tree of the central row of each replicate, the other trees serving as borders. All the measurements were taken in the same tree in each replicate. Values for each day and replicate were averaged before the mean and the standard error were calculated.

Considering that the relationship between the series of predictor or explanatory variables (GR, PAR, Ta, Tc, RH, VPD and ET_0) and the response variable (SF) is linear, the experiment was designed as a simple linear regression analysis [20]. As the predictor variables are random, the method used was reduced major axis (RMA) regression. Regression lines between the three data sets representing the three levels of the canopy were compared using the analysis of covariance. To model the relationship between the series of predictor/explanatory variables (Rs, Ta, Tc, VPD and ET_0) and the response variable (SF), regressions of various orders were computed using R statistical software. Regression lines were compared using various statistical techniques from R packages.
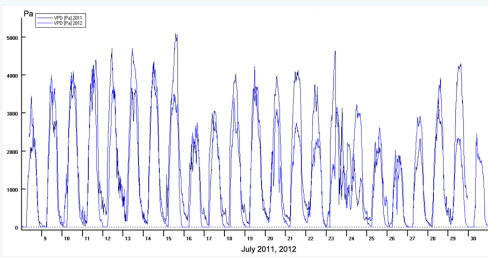
Results and Discussion
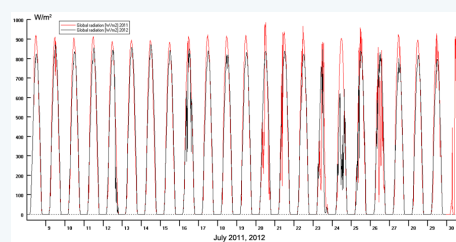
Figure 1a: Dynamics of global radiation Rs, during the measurement period (8 - 30 July 2011 and the same period in 2012)
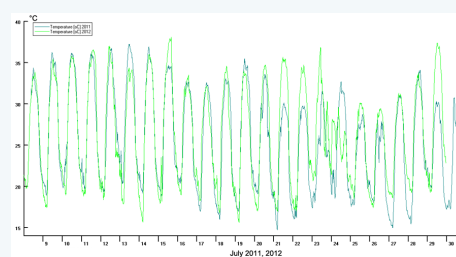
Figure 1b: Dynamics of canopy temperature Tc, during the measurement period (8 - 30 July 2011 and the same period in 2012).

Figure 1c: Dynamics of vapour pressure deficit VPD during the measurement period (8 - 30 July 2011 and the same period in 2012).
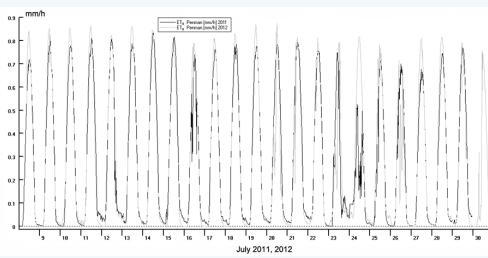
Figure 1d: Dynamics of reference evapotranspiration ET0 during the measurement period (8 - 30 July 2011and the same period in 2012).

All the parameters concerning the evaporative demand where relatively constant during the measurement period with an obvious daily fluctuation trend (Figure 1a-1d). During the experimental period, in both years, there was not rainfall event allowing us to maintain the water stress conditions in the experimental site area. Rs levels were high with maximum levels as high as 986.7 and 871.8 W/m^2 for 2011 and 2012 respectively and averages 292.3 and 281.3 W/m^2, totaling 2171 and 2109 W/m^2 for the entire period of measurement (Figure 1a).
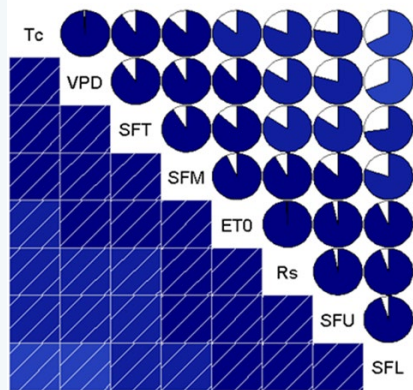

Figure 2: Correlogram of intercorrelations.

Mean daily air temperature (Tm) and midday air temperature (Tmd) presented a similar daily trend. During the experiment, average Tm and average daily minimum temperatures were 25 and 13°C, respectively (Figure 1b), and average mean relative humidity was 66%. Mean VPD values presented a similar seasonal trend (Figure 1c). Intercorrelations shown in Figure 2 using a correlogram indicate a stronger correlation of SF_{low} and

SF_{upper} with Rs and ET_0 and less with VPD and Tc whilst for SF_{middle} a higher correlation with VPD and ET_0. SF_{tree} was more correlated with VPD and Tc. In general, increases in predictor variables were associated with increases in SF until reaching high values, after which SF levelled off as they increased, thus, departing from linearity.

The correlogram in Figure 2 shows intercorrelations between sap flow (SF) at various levels of the canopy (SF_{Low}, SF_{Middle}, SF_{Upper} and of the whole tree (SF_{Tree}) and environmental parameters (Rs, Tc, VPD, ET_0). Rows and columns have been reordered using principal components analysis (PCA). All correlations are positive (blue); the darker and more saturated the color, the greater the magnitude of the correlation. The upper triangle of cells displays the same information using pies. The strength of the correlation is displayed by the size of the filled pie slice. Positive correlations fill the pie starting at 12 o'clock and moving in a clockwise direction.

Residuals versus Fitted graph indicates evidence of curved relationship, suggesting the addition of the quadratic or cubic term. Thus, best-fit curve using polynomial regression, a second-order (quadratic) and third-order (cubic) yielding equations with a higher determination coefficient. However, only in few cases these coefficients were significantly higher. The study confirmed that Ta [21,22] and Tc are not an accurate indicator of the evaporative demand of the atmosphere. (Figure 3) Probability plot of studentized residuals against a t distribution with n-p-l degrees of freedom (n = sample size, p = number of regression parameters, including intercept). A 95 per cent confidence envelope is produced using a parametric bootstrap.
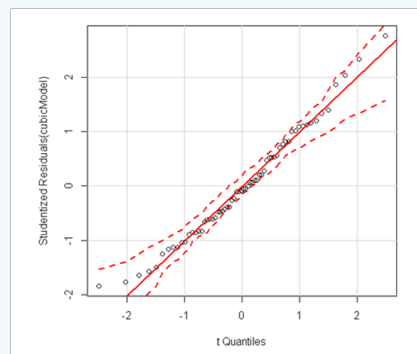
Figure 3: Reference evaportranspiration against sap flow of the entire tree.
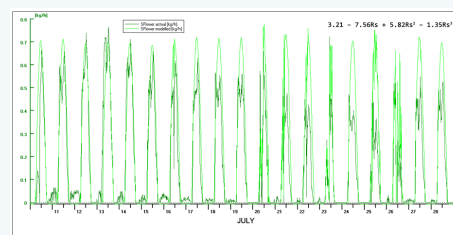
Figure 4a: Simulation of best-fit regression models between sap flows at the lower canopy level.

Of the relationships between the water status indicator (SF) and the predictor variables (covariates), Ta presented the weakest r^2 value. In general, a cubic fit of the regression between SF and environmental variables yielded equations with a determination coefficient higher than those found for the first and second order regressions. However, it was statistically significant only in few cases described below. For the lower part of the apple canopy (Figure 4a), the cubic fit regression between SF and Rs was characterized by a higher correlation ($r^2 = 0.91$) than other predictors, especially Ta and VPD ($r^2 = 0.49$ and 0.48 respectively). SF was also highly related to changes in ET_0 ($r^2 = 0.87$).
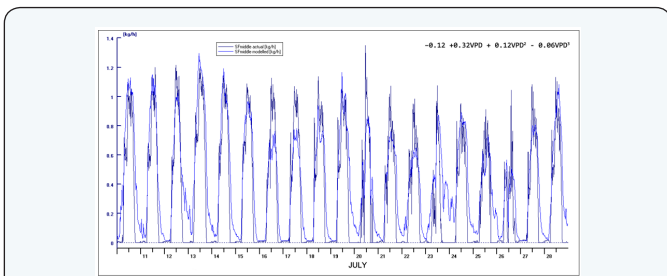

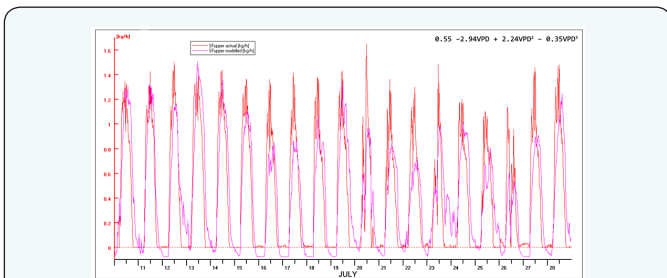**Figure 4b:** Simulation of best-fit regression models between sap flows at the middle canopy level.

Figure 4c: Simulation of best-fit regression models between sap flows at the upper canopy level.
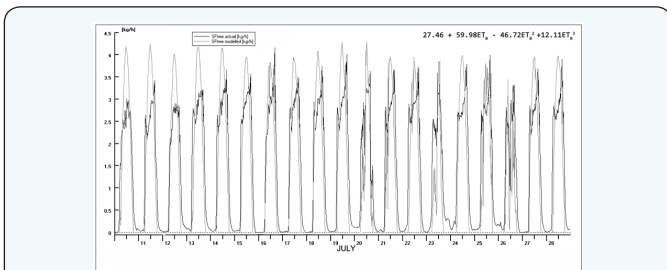

Figure 4d: Simulation of best-fit regression models between sap flow at the entire apple tree level and the respective evaporative demand parameter.

Regressions of SF values of the middle part of the canopy (Figure 4b) against evaporative demand parameters found that VPD, ET_0 and Rs could predict almost similarly SF ($r^2 = 0.89$, 0.88 and 0.86 respectively). As for the lower part of the canopy, Ta was not a good predictor. The regression analysis for the purposes of modelling SF of the upper part of the apple canopy (Figure 4c) found again VPD, Rs and ET_0 as very good predictors of SF also for this part of the canopy ($r^2 = 0.95$, 0.95 and 0.94). Again, Ta was not a well correlated with SF (Figure 4d).

Conclusion

The above mentioned results indicate that baselines or reference values for sap flow rate as a plant-based water status indicators can be obtained for apple trees, even though there was a certain scattering in the relations between the plant-based measurements and the environmental variables. The regression analysis indicated that the highest coefficients of determination were obtained for the regressions of S_{Flow} against Rs, SF_{middle} and SF_{upper} against VPD and SF_{tree} against ET_0. However, these correlations must be used within their confidence levels.

Notwithstanding, at the current level of this research, the best-fit regression approach of modeling can offer a proxy of daily SF values but, in general, they hardly simulate the daily SF dynamics, especially when the evaporative parameters highly fluctuate during the day or especially for the middle and bottom part of the canopy. This gross estimation of SF could be used in automatic irrigation scheduling in apple trees [23].

References

1. Kullaj E, Domi H, Spahiu T, Thomaj F (2014) Behaviour of apple cultivars under a high radiation and temperature regime of Western Plain in Albania. Acta Horticulturae (ISHS) 1038(51): 423-428.

2. Thoma, D, Kullaj E (2014) Selection of flood-tolerant Prunus rootstocks using sap flow. Agriculture and Forestry 60(4): 111-117.

3. Nobel PS (1991) Physicochemical and environmental plant physiology. Academic Press, San Diego pp. 635.

4. Jarvis PG, McNaughton KG (1986) Stomatal control of transpiration: Scaling up from leaf to region. Advanced Ecological Reseearch 15: 1-49.

5. Pieruschka R, Huber G, Berry JA (2010) Control of transpiration by radiation PNAS 107(30): 13372-13377.

6. Thoma D, Kullaj E (2015a) Stomatal response kinetics in various apple cultivars under a high radiation environment. Proceedings of the 25th Intl. Scientific-Experts Congress on Agriculture and Food Industry, Izmir, Turkey 25-27/04/2014

7. Monteith JL, Unsworth MH (1990) Principles of environmental physics. Edward Arnold, London pp. 291.

8. Jones HG (1992) Plants and microclimate: a quantitative approach to environmental plant physiology. (2nd edn), Cambridge University Press, Cambridge pp. 428.

9. Jurik TW Kliebenstein H (2000) Canopy architecture, light extinction and self-shading of a prairie grass, Andropogon gerardii. Am Midl Nat 144(1): 51-65.

10. Parker GG, Davis MM, Chapotin SM (2002) Canopy light transmittance in Douglas fir/western hemlock stands. Tree Physiology 22(2-3): 147-157.

11. Domi H, Kullaj E, Spahiu T, Thomaj F (2014) Xylem dynamics of different rootstock/scion combinations of apple under a hot, semi-arid Mediterranean climate. Acta Horticulturae (ISHS) 1038(46): 387-392.

12. Domi H, Spahiu T, Kullaj E, Thomaj F (2013) Influence of M9 rootstock on the reproductive behaviour of apple cultivars under dry, semi-arid growing conditions. Agro-Knowledge Journal 14(1): 5-10.

13. Sinoquet H, Sonohat G, Phattaralerphong J, Godin C (2005) Foliage randomness and light interception in 3-D digitized trees: an analysis from multi scale discretization of the canopy. Plant, Cell and Environment 28(9): 1158-1170.

14. Massonnet C, Regnard JL, Lauri PE, Costes E, Sinoquet H (2008) Contributions of foliage distribution and leaf functions to light interception, transpiration and photosynthetic capacities in two apple cultivars at branch and tree scales. Tree Physiology 28(5): 665-678.

15. Costes E, Sinoquet H, Godin C, Kelner J (1999) 3D digitizing based on tree topology: application to study the variability of apple quality within the canopy. Acta Horticulturae 499(31): 271-280.

16. Godin C, Costes E, Sinoquet H (1999) A method for describing plant architecture with integrates topology and geometry. Annals of Botany 84(3): 343-357.

17. Costes E, Lauri PE, Regnard JL (2006) Analyzing fruit tree architecture: implications for tree management and fruit production. Horticultural Reviews 32: 1-61.

18. Lindroth A, Čermák J, Kučera J, Cienciala E, Eckersten H (1995) Sap flow by the heat-balance method applied to small-size salix trees in a short-rotation forest. Biomass and Bioenergy 8: 7-15.

19. Čermak J, Kučera J, Nadezhdina N (2004) Sap flow measurements with some thermodynamic methods, flow integration within trees and scaling up from sample trees to entire forest stands Trees 18(5): 529-546.

20. Thoma D, Kullaj E (2015b) transpiration model to screen local fruit tree genotypes for drought tolerance. 5th Int. Scientific Agricultural Symposium Jahorina, Bosnia & Hercegovina 23-26/10/2014.

21. Hatfield & Fuchs (1990) Evapotranspiration models. In Management of Farm Irrigation Systems. Eds. G.J. Hoffman, T A Howell and K H Solomon ASAE Monograph, St. Joseph, pp. 33-60.

22. Ortuño MF, García-Orellana, Conejero W, Ruiz-Sánchez MC, Mounzer O, et al. (2006) Relationships between climatic variables and sap flow, stem water potential and maximum daily trunk shrink age in lemon trees. Plant and Soil 279(1): 229-242.

23. Thoma D, Kullaj E (2015c) Characterization of stomatal sensitivity to water deficits of several apple genotypes. Proceedings of the 25th Intl. Scientific-Experts Congress on Agriculture and Food Industry, Izmir, Turkey 25-27/04/2014.