

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	VI
DECLARATION	VII
ABSTRACT	VIII
LIST OF FIGURES	X
LIST OF ABBREVIATIONS AND SYMBOLS	XXIII
CHAPTER 1 : GENERAL INTRODUCTION	1
1.1 BACKGROUND AND RELEVANCE OF THE STUDY	1
1.2 MAIN HYPOTHESES	4
1.3 AIM OF THE STUDY	5
1.4 OBJECTIVES	5
CHAPTER 2 : LITERATURE REVIEW	7
2.1 PRODUCTION OF TREE NUT CROPS	7
2.2 MORPHOLOGICAL, PHYSIOLOGICAL AND ANATOMICAL CHARACTERISTICS OF DECIDUOUS AND EVERGREEN TREE NUT CROPS IN RELATION TO CROP WATER USE	10
2.3 FACTORS AFFECTING GROWTH, PHYSIOLOGY AND CROP WATER USE.....	12
2.3.1 <i>Environmental conditions</i>	12
2.3.2 <i>Boundary layer and physiological conductances</i>	14
2.3.3 <i>Hydraulic flow resistances</i>	17
2.3.4 <i>Orchard management practices</i>	19
2.4 MEASUREMENT OF CROP WATER USE.....	20
2.4.1 <i>Hydrological approaches</i>	20
2.4.1.1 Lysimetry	20
2.4.1.2 Soil water balance	21
2.4.2 <i>Micrometeorological approaches</i>	23
2.4.2.1 Bowen ratio energy balance	23
2.4.2.2 Eddy covariance	25
2.4.2.3 Surface renewal method.....	28

2.4.3.1 Remote sensing energy balance method	30
2.4.4 <i>Plant physiology approaches</i>	30
2.4.4.1 Chamber systems.....	30
2.4.4.2 Sap flow methods	31
2.4.5 <i>Measured water use for various tree nut crops</i>	35
2.5 CROP WATER USE MODELLING	37
2.5.1 <i>Soil water balance approach</i>	38
2.5.2 <i>Crop coefficient approach</i>	40
2.5.3 <i>Stomatal conductance approach</i>	46
2.6 CONCLUSIONS.....	51
CHAPTER 3 : GENERAL MATERIALS AND METHODS.....	54
3.1 DESCRIPTION OF EXPERIMENTAL SITES	54
3.1.1 <i>Cullinan experimental site</i>	54
3.1.2 <i>Hatfield experimental site</i>	55
3.1.3 <i>White River experimental site</i>	56
3.2 FIELD MEASUREMENTS	57
3.2.1 <i>Fractional interception of photosynthetically active radiation by the canopy</i>	57
3.2.2 <i>Meteorological measurements</i>	58
3.2.3 <i>Soil water content measurements</i>	59
3.2.4 <i>Irrigation scheduling monitoring</i>	63
3.2.5 <i>Crop evapotranspiration measurements</i>	65
3.2.6 <i>Soil evaporation measurements</i>	68
3.2.7 <i>Measurements and calibration of sap flow</i>	72
CHAPTER 4 : ENVIRONMENTAL CONTROL OF TRANSPIRATION IN IRRIGATED PECAN AND MACADAMIA TREES.....	76
4.1 INTRODUCTION.....	76
4.2 MATERIALS AND METHODS.....	79
4.2.1 <i>Calculation of canopy and aerodynamic conductances and the decoupling coefficient</i>	79

4.2.2 Sensitivity analysis of transpiration to variations in environmental factors.....	80
4.3 RESULTS AND DISCUSSION	82
4.3.1 Aerodynamic and canopy conductances, and resultant decoupling coefficient.....	82
4.3.2 Daily variations of canopy transpiration in response to daily changes in the atmospheric environment.....	85
4.3.3 The response of canopy transpiration to the individual effects of different environmental variables.....	88
4.3.4 The response of canopy transpiration to an increase in atmospheric evaporative demand under various atmospheric conditions.....	94
4.3.5 Manipulation of water loss by pecan and macadamia trees under non-limited soil water conditions.....	97
4.4 CONCLUSIONS.....	98

CHAPTER 5 : MODELLING DAILY TRANSPIRATION OF PECANS AND MACADAMIAS UNDER NON-LIMITING SOIL WATER CONDITIONS 100

5.1 INTRODUCTION.....	100
5.2 MATERIALS AND METHODS.....	102
5.2.1 Field measurements	102
5.2.1.1 Proportion of shaded ground area and sunflecks within the shaded area.....	102
5.2.1.2 Hourly measurements of transmitted solar irradiance and its conversion to transmitted photosynthetically active radiation	103
5.2.2 Crop modelling.....	105
5.2.2.1 Modelling of daily fractional photosynthetically active radiation intercepted by the canopy.....	105
5.2.2.2 Modelling of daily transpiration using the FAO-56 dual crop coefficient approach.....	111
5.2.2.3 Modelling of daily transpiration using a canopy conductance model.....	112
5.2.3 Sensitivity analyses of daily transpiration modelling input parameters..	113

5.3 RESULTS AND DISCUSSION	115
5.3.1 Hourly and daily radiation interception modelling.....	115
5.3.2 Daily transpiration estimates using the FAO-56 dual crop coefficient procedure	120
5.3.3 Daily transpiration estimates using a canopy conductance model.....	126
5.3.4 Sensitivity analyses for the FAO-56 and canopy conductance transpiration models	133
5.4 CONCLUSIONS.....	135

CHAPTER 6 : SOIL EVAPORATION IN PECAN AND MACADAMIA

ORCHARDS	137
6.1 INTRODUCTION.....	137
6.2 MATERIALS AND METHODS.....	140
6.2.1 Modelling of soil evaporation using the FAO-56 dual K_c approach	140
6.2.2 Sensitivity analyses of daily soil evaporation modelling input parameters	144
6.2.2 Soil evaporation modelling scenarios.....	146
6.3 RESULTS AND DISCUSSION	148
6.3.1 Spatial and temporal variability of measured soil evaporation	148
6.3.1.1 Spatial variation of daily soil evaporation within and outside the irrigated area.....	148
6.3.1.2 Temporal variability of soil evaporation	153
6.3.2 Parameterization and validation of the FAO-56 dual K_c model	157
6.3.3 Sensitivity analyses of the different model input parameters	159
6.3.4 Estimation of soil evaporation throughout the entire experimental period	161
6.3.5 Scenarios of soil evaporation modelling.....	166
6.4 CONCLUSIONS.....	167

CHAPTER 7 : EVAPOTRANSPIRATION OF PECANS AND MACADAMIAS ...

7.1 INTRODUCTION.....	169
7.2 MATERIALS AND METHODS.....	171

7.2.1 Quantification of actual evapotranspiration of pecan and macadamia trees	171
7.2.2 Modelling of monthly crop evapotranspiration using single crop coefficient approaches	172
7.2.2.1 The generic FAO-56 model	172
7.2.2.2 A crop-specific modelling approach	174
7.3 RESULTS AND DISCUSSION	177
7.3.1 Crop evapotranspiration and crop coefficients throughout the growing season	177
7.3.2 Evapotranspiration partitioning	182
7.3.3 Water use efficiency	185
7.3.4 Crop evapotranspiration estimates using a single crop coefficient approach	186
7.3.4.1 Modelling ET of pecans using the generic FAO-56 model applied to stone fruit	186
7.3.4.2 Modelling ET of pecans using a crop-specific modelling approach	188
7.3.4.3 Modelling ET of macadamias using the generic FAO-56 model with crop coefficients applied to citrus and macadamia-specific crop coefficients	193
7.4 CONCLUSIONS	197
CHAPTER 8 : GENERAL CONCLUSIONS AND RECOMMENDATIONS.....	201
8.1 CONCLUSIONS	201
8.2 RECOMMENDATIONS FOR FUTURE RESEARCH	206

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DECLARATION

I, Nádia Alcina Ibraimo, declare that the thesis, which I hereby submit for the degree Ph.D. Agronomy at the University of Pretoria, is my own work and has not been previously submitted by me for a degree at this or any other tertiary institution. Where secondary material is used, this has been carefully acknowledged and referred in accordance with the university requirements. I am aware of the university policy and implications regarding plagiarism.

SIGNATURE:

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ABSTRACT

Water use of deciduous and evergreen tree nut crops: a case study using pecans and macadamias

by

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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, through accurate quantification of crop water use or evapotranspiration (ET, composed by soil evaporation – E_s and transpiration - T), becomes a vital factor for maximization of orchard profitability. The ET of fruit tree species is highly variable and is affected by several factors including changes in climate and orchard management practices. Direct measurements of crop ET are practically impossible under all possible conditions, and thus crop modelling is required to estimate water use for different scenarios. The selection of an appropriate modelling approach to address a specific situation requires an understanding of the regulation of T and E_s , as affected by the variability in the driving factors. This study investigated the regulation of water use in two tree nut species, with contrasting growth habits (pecans a deciduous species and macadamias an evergreen species) in order to identify the most suitable crop modelling approaches to estimate the water use of these crops, for improved irrigation scheduling and planning. Field trials were conducted for two to three consecutive growing seasons in a 7-year-old pecan orchard at Hatfield, a 37-year-old pecan orchard at Cullinan and a 6-year-old macadamia

orchard at White River. Measurements included T (heat ratio method), crop ET (eddy covariance technique), E_s (micro-lysimeters), weather variables (automatic weather stations installed on-site), changes in soil water content (TDR100 system) and solar irradiance transmittance through the canopy (Delta-T tube solarimeters). Field measurements were used to investigate the environmental control of T using a quantile regression approach, as well as for parameterization and validation of the following modelling approaches: FAO-56 single and dual crop coefficient (K_c), radiation interception by the canopy and canopy conductance models. Transpiration normalised for canopy size was well-coupled to the atmosphere in both pecans and macadamias, and primarily driven by vapour pressure deficit (VPD), with T rates of both crops decreasing considerably once a threshold VPD had been reached (1.4 kPa for pecans and 1.2 kPa for macadamias), indicating the presence of a strong stomatal control during these periods. Despite such similarity in their process of water use, pecans and macadamias showed slightly different mechanisms of crop water use at relatively lower levels of VPD, with T being primarily demand-limited in pecans and supply-limited in macadamias. The common presence of strong stomatal control in both crops is typically associated with high coupling of T to the atmosphere in tall deciduous and evergreen perennial tree crops, while their slightly distinct crop water use patterns are likely related to their varying growth habits. Daily T of pecans and macadamias was accurately predicted with a canopy conductance model parameterized for each crop, while daily E_s beneath the canopy was accurately obtained with the FAO-56 dual K_c model. These daily estimates could contribute greatly to improved irrigation scheduling of these orchard crops. While daily predictions of T and E_s required the use of relatively more complex modelling approaches, monthly estimates of ET were accurately obtained for these crops using simple, single K_c modelling approaches, which can significantly contribute to improved irrigation planning and water resources management for the respective orchard crops. Monthly ET of pecans was, however, more accurately predicted with a crop-specific single K_c model, while a generic model using crop-specific K_c values was sufficient to provide accurate predictions of monthly ET of macadamias.

LIST OF FIGURES

- Figure 2.1** Top ten world-producing countries of tree nut crops (INC, 2015c). 8
- Figure 2.2** Effect of changing physiological conductances on transpiration from different crops. Note the greater sensitivity of transpiration to physiological conductance in tall crops such as forests or (Jones *et al.* 1985). 15
- Figure 2.3** The components of a soil water balance system. The inputs to the system are rainfall, irrigation and the water brought by capillary rise from a ground water-table to the root zone, while the outputs are transpiration, soil evaporation, runoff and deep percolation. Changes in soil water content due to subsurface flow may contribute to the system as either an input or output (Allen *et al.* 1998). 22
- Figure 2.4** Schematic diagram showing the configurations of heat-pulse probes implanted radially in a stem (Bleby *et al.* 2004). For the CHPM, the downstream temperature is installed at a distance x_1 above the heater and the upstream probe at a distance x_2 below the heater. For the HRM, temperature probes are installed at the same distance x above and below the heater, which is typically 5 mm. Temperature sensors (Type-T thermocouples) are located at various depths in the conducting sapwood below the sapwood-cambium boundary). 33
- Figure 3.1** The mixed cultivar pecan orchard at Cullinan..... 55
- Figure 3.2** The mixed cultivar pecan orchard at Hatfield. 56
- Figure 3.3** The 'Beaumont' macadamia orchard in White River. 57
- Figure 3.4** Relationship between measurements of fractional interception of photosynthetically active radiation (f_{IPAR}) and effective fractional cover ($f_{c\ eff}$)

in the young pecan orchard at Hatfield and young macadamia orchard in White River.....	58
Figure 3.5 Automatic weather station installed in the macadamia orchard at White River experimental site.....	59
Figure 3.6 Installation of TDR100 soil water sensors at various depths and positions around a representative tree in the (A) pecan orchard in Cullinan and (B) macadamia orchard in White River.	60
Figure 3.7 Placement of TDR probes in the pecan orchard at Cullinan site, to account for variability in wetting and shading within the area allocated to each tree, for measurements of volumetric soil water content.	61
Figure 3.8 Placement of TDR probes in the macadamia orchard at White River site, to account for variability in wetting and shading within the area allocated to each tree, for measurements of volumetric soil water content.....	62
Figure 3.9 Cumulative water supply (rainfall – R plus irrigation – I) in comparison to grass reference evapotranspiration (ET_o) and crop water use (evapotranspiration – ET, transpiration – T and soil evaporation – E_s) for the 37-year-old pecan orchard during the 2011/2012 growing season at Cullinan.	64
Figure 3.10 Cumulative water supply (rainfall – R plus irrigation – I) in comparison to grass reference evapotranspiration (ET_o) and crop water use (evapotranspiration – ET, transpiration – T and soil evaporation – E_s) for the 6-year-old macadamia orchard during the 2011/2012 growing season at White River.....	64
Figure 3.11 Position of the Open Path Eddy Covariance system on (A) scaffolding in the centre of the pecan orchard and (B) a lattice mast in the macadamia orchard.	65

Figure 3.12 Surface energy balance closure for the mature pecan orchard at Cullinan during February 2012. Data are paired 30 min averages. The 1:1 line (dotted line) is provided together with the regression equation and coefficient of determination for the best-fit line through the data. 67

Figure 3.13 The surface energy balance closure for the macadamia orchard during (A) winter, (B) spring, (C) summer and (D) autumn window periods of measurements. Data are paired 30 min averages. The 1:1 line (dotted line) is provided together with the regression equation and coefficient of determination for the best-fit line through the data. 68

Figure 3.14 Micro-lysimeters used for soil evaporation measurements in ‘Beaumont’ macadamia orchard at White River experimental site. 69

Figure 3.15 Placement of micro-lysimeters in the mature pecan orchard at Cullinan site for measurements of soil evaporation. A₁ to A₁₂ represent different wetted and shaded soil surface areas within the ground area allocated to one tree. 70

Figure 3.16 Placement of micro-lysimeters in the young pecan orchard at Hatfield site for measurements of soil evaporation. A₁ to A₇ represent different wetted and shaded soil surface areas within the ground area allocated to one tree. 71

Figure 3.17 Placement of micro-lysimeters in the macadamia orchard at White River site for measurements of soil evaporation. A₁ to A₉ represent different wetted and shaded soil surface areas within the ground area allocated to one tree. 71

Figure 3.18 Heat pulse velocity system measuring sap flow in ‘Beaumont’ macadamia trees during the 2010 – 2012 growing period at the White River experimental site. 72

Figure 3.19 Comparison between transpiration estimated as the difference between simultaneous measurements of crop evapotranspiration and soil evaporation ($T_{residual}$) and calibrated sap flow measurements ($T_{sap\ flow}$) conducted (A) in the mature pecan orchard at Cullinan in February 2012 and (B) in the macadamia orchard at White River for three days during winter, summer and autumn seasons. The dotted line is the 1:1 line. 75

Figure 4.1 Relationships between daily estimates of the (A, C) decoupling coefficient (Ω) and canopy conductance (g_c) and the (B, D) decoupling coefficient and aerodynamic conductance (g_a) for pecans and macadamias, respectively. Data shown correspond to 32 days of measurements in the pecan orchard and 23 days of measurements in the macadamia orchard. 83

Figure 4.2 Daily variations in canopy transpiration - T_c (dotted line) in response to daily changes in (A, F) wind speed – u_2 , (B, G) air temperature - T_a (C, H) vapour pressure deficit - VPD, (D, I) solar radiation - R_s and (E, J) atmospheric evaporative demand - ET_o (solid lines) for pecans during the 2010/2011 growing season and macadamias during the 2011/2012 growing season. 86

Figure 4.3 Changes in transpiration crop coefficients (K_t) for (A) pecans throughout the 2010/2011 growing season and (B) macadamias throughout the 2011/2012 growing season, for the period when the trees were in leaf... 88

Figure 4.4 Canopy transpiration (T_c) as influenced by daily changes in volumetric soil water content (θ) for (A) pecan and (B) macadamia trees. Only selected regression quantiles of the distribution of daily canopy transpiration were plotted, namely 0.1 (black circles), 0.5 (open squares) and 0.9 (black triangles)..... 89

Figure 4.5 Canopy transpiration - T_c as influenced by daily changes in (A, E) wind speed – u_2 , (B, F) mean air temperature - T_a , (C, G) vapour pressure deficit - VPD and (D, H) solar radiation - R_s for pecan and macadamia trees. Only selected regression quantiles of the distribution of daily canopy

transpiration were plotted, namely 0.1 (black circles), 0.5 (open squares) and 0.9 (black triangles). The regression equation represents the 0.9 quantile..... 90

Figure 4.6 Average response of canopy transpiration (T_c) at the most extreme regression quantile to daily changes in atmospheric evaporative demand (ET_o) at (A, F) the whole range of prevailing conditions, (B, G) low levels of VPD and R_s , (C, H) low VPD and high R_s , (D, I) high VPD and low R_s , (E, J) high VPD and high R_s for pecans and macadamias, respectively. The equation and R^2 for the best curve fit are provided for each set of conditions. 95

Figure 5.1 Measurement of shaded and sunflecks areas beneath the canopy of 7-year-old pecan trees at the Hatfield experimental site..... 103

Figure 5.2 Hourly measurements of global solar radiation penetration through the canopy using Delta-T tube solarimeters positioned at various distances from the 37-year-old pecan tree row (0 m, 2 m and 4.5 m NNE – SSW) at the Cullinan experimental site, between 19 February and 02 March 2012. 104

Figure 5.3 Schematic representation of a fruit-tree orchard showing model input variables related to orchard configuration, canopy dimensions, and canopy porosity. Also shown is the interaction between solar rays (---) and the trees when: (1) the beam passes unobstructed below the canopy; (2) the beam passes unobstructed through gaps in the canopy, thus observable as a sunfleck on the shaded ground area (C_P); (3) the beam passes by the edge of the canopy, thus casting a shadow (Oyarzun *et al.* 2007)..... 105

Figure 5.4 Comparison between measured (dotted line) and simulated (solid line) hourly fractional intercepted photosynthetically active radiation (f_{IPAR}) on (A) 25 February 2012 in the 37-year-old pecan orchard at Cullinan, (B) 15 April 2014 in the 7-year-old pecan orchard spaced at 10 m x 10 m at Hatfield, (C) 01 April 2014 in the 7-year-old pecan orchard spaced at 10 m

x 5 m at Hatfield and (D) 27 January 2012 in the 6-year-old macadamia orchard at White River..... 116

Figure 5.5 Comparison between measured (open circle symbols) and simulated (closed circle symbols) daily fractional intercepted photosynthetically active radiation (f_{IPAR}) for a (A) 37-year-old pecan orchard between 19 February and 12 March 2012, (B) 7-year-old pecan orchard spaced at 10 m x 10 m between 11 and 17 April 2014, (C) 7-year-old pecan orchard spaced at 10 m x 5 m between 01 and 07 April 2014 and (D) 6-year-old macadamia orchard between 26 and 30 January 2012. 117

Figure 5.6 Comparison between measured (symbols) and simulated (solid line) daily fractional intercepted photosynthetically active radiation (f_{IPAR}) for a 37-year-old pecan orchard during the (A) 2009/2010 season, (B) 2010/2011 season and (C) 2011/2012 season at the Cullinan study site..... 118

Figure 5.7 Comparison between measured (symbols) and simulated (solid line) daily fractional intercepted photosynthetically active radiation (f_{IPAR}) for a 6-year-old macadamia orchard during the (A) 2010/2011 season and (B) 2011/2012 season at the White River study site. 120

Figure 5.8 Comparison between daily measured and simulated transpiration crop coefficients (K_t) for the 37-year-old pecan orchard for (A) parameterization and (B) validation of the FAO-56 model. 121

Figure 5.9 Comparison between daily measured and simulated transpiration (T) for the 37-year-old pecan orchard for (A) parameterization and (B) validation of the FAO-56 model. 122

Figure 5.10 Comparison between daily measured and simulated transpiration crop coefficients (K_t) for the 6-year-old macadamia orchard for (A) parameterization and (B) validation of the FAO-56 model..... 123

Figure 5.11 Comparison between daily measured and simulated transpiration (T) for the 6-year-old macadamia orchard for (A) parameterization and (B) validation of the FAO-56 model.	124
Figure 5.12 Daily leaf resistance (r_l) parameter of a 37-year-old, closed-canopy pecan orchard during the 2010/2011 and 2011/2012 growing seasons.	125
Figure 5.13 Comparison between daily measured and simulated transpiration (T) for the 37-year-old pecan orchard for (A) parameterization and (B) validation of the canopy conductance model.	129
Figure 5.14 Comparison between daily measured and simulated transpiration (T) for the 6-year-old macadamia orchard for (A) parameterization and (B) validation of the canopy conductance model.	130
Figure 5.15 Running average daily transpiration (T) of the well-watered pecan orchard during the 2011/2012 growing season estimated using the canopy conductance model on a (A) seven and (B) 14-day time step at the Cullinan study site.	132
Figure 5.16 Running average daily transpiration (T) of well-watered macadamia trees during the 2011/2012 growing season estimated using the canopy conductance model on a (A) seven and (B) 14-day time step at the White River study site.	133
Figure 6.1 Daily average (A) volumetric soil water content (θ) in the top surface layer (0 – 15 cm) and rooting density (RD) and (B) soil evaporation (E_s) at various positions away from a 37-year-old micro-sprinkler irrigated pecan tree, measured for 10 days during February and March 2012 at the Cullinan experimental site.	149
Figure 6.2 Daily average soil evaporation (E_s) at various positions away from a 7-year-old drip irrigated pecan tree, measured for seven days during April 2013 at the Hatfield experimental site.	150

Figure 6.3 Changes in (A) volumetric soil water content (θ) in the top surface layer (0 – 15 cm) and (B) average daily soil evaporation (E_s) at various positions across the row (on the road area covered by grass - G, furrow - F, ridge - R and under the dripper - UD, on both sides of the tree row, west - W and east - E, as well as in the centre of the tree row in between the drippers - ID) of a 6-year-old drip irrigated macadamia orchard, for three to four days during winter, summer and autumn measurement periods in the 2011/2012 growing season at the White River experimental site..... 152

Figure 6.4 Daytime changes in soil evaporation (E_s) as influenced by hourly fluctuations in atmospheric evaporative demand (ET_o) and volumetric soil water content (θ) of the top surface layer, on typical sunny days between 21 and 23 February 2012 (A to C, respectively), in the 37-year-old pecan orchard at Cullinan. 154

Figure 6.5 Linear dependency of daytime fluctuations of soil evaporation (E_s) on different atmospheric variables, namely (A) solar radiation - R_s , (B) mean air temperature - T_a , (C) wind speed – u_2 and (D) vapour pressure deficit - VPD in the 37-year-old pecan orchard at Cullinan. 155

Figure 6.6 Changes in soil evaporation (E_s) for five consecutive days following an irrigation event of 32 mm in the mature pecan orchard at the Cullinan site, as influenced by fluctuations in reference evapotranspiration (ET_o) and volumetric water content (θ) of the first 0 – 15 cm soil layer. The two stages of E_s are also illustrated, whereby E_s proceeds at maximum rates when θ is not limiting (stage 1 – energy limiting stage), followed by E_s limited by the availability of water in the top soil layer (stage 2 - falling rate stage)..... 156

Figure 6.7 FAO-56 dual K_c model for a sandy soil in the mature pecan orchard (parameterization – A; validation – B), sandy clay loam soil for the young pecan orchard (parameterization – C; validation – D) and sandy loam soil for the macadamia orchard (parameterization – E; validation – F)..... 158

- Figure 6.8** Daily soil evaporation (E_s) estimated using the FAO-56 dual K_c model for the (A) 2009/2010, (B) 2010/2011 and (C) 2012/2012 growing seasons in the mature, micro-sprinkler irrigated pecan orchard at Cullinan, as affected by changes in atmospheric evaporative demand (ET_o), canopy cover ($f_{c\ eff}$) and rainfall and irrigation events..... 162
- Figure 6.9** Daily soil evaporation (E_s) estimated using the FAO-56 dual K_c model in drip irrigated, young pecan trees, spaced at (A) 10 m x 10 m and (B) 5 m x 10 m, as affected by changes in atmospheric evaporative demand (ET_o), canopy cover ($f_{c\ eff}$) and rainfall and irrigation events during the 2012/2013 growing season at Hatfield. 164
- Figure 6.10** Daily soil evaporation (E_s) estimated using the FAO-56 dual K_c model in the drip irrigated, young macadamia orchard as affected by changes in atmospheric evaporative demand (ET_o) and rainfall and irrigation events during the (A) 2010/2011 season and (B) 2011/2012 season at the White River experimental site. 165
- Figure 6.11** Seasonal soil evaporation (E_s) modelled under different scenarios of orchard-floor management in different experimental orchards. 166
- Figure 7.1** Monthly actual evapotranspiration (ET) and crop coefficients (K_c) of a 37-year-old pecan orchard during the (A) 2009/2010, (B) 2010/2011 and (C) 2011/2012 seasons, in relation to atmospheric evaporative demand (ET_o) and fractional interception of photosynthetically active radiation (f_{IPAR})..... 179
- Figure 7.2** Monthly actual evapotranspiration (ET) and crop coefficients (K_c) of a 6-year-old macadamia orchard during the (A) 2010/2011 and (B) 2011/2012 seasons, in relation to atmospheric evaporative demand (ET_o) and fractional interception of photosynthetically active radiation (f_{IPAR}). 182
- Figure 7.3** Partitioning of crop evapotranspiration (ET) into whole-tree transpiration (T) and soil evaporation (E_s) in the 37-year-old pecan orchard during three

consecutive seasons of measurement (2009/2010, 2010/2011 and 2011/2012) at the Cullinan experimental site and in the 7-year-old pecan orchard during the 2012/2013 growing season at the Hatfield experimental site..... 183

Figure 7.4 Partitioning of crop evapotranspiration (ET) into whole-tree transpiration (T) and soil evaporation (E_s) in the 6-year-old macadamia orchard during two consecutive seasons of measurement (2010/2011 and 2011/2012) at the White River experimental site..... 184

Figure 7.5 Comparison between monthly actual and estimated crop evapotranspiration (ET) using the generic procedure of FAO-56 with climate adjusted single (time-averaged) K_c values published for stone fruits for a mature pecan orchard during the (A) 2009/2010 season, (B) 2010/2011 season and (C) 2011/2012 season at the Cullinan experimental site..... 187

Figure 7.6 A six stage crop coefficient (K_c) curve observed for a well-managed, mature pecan orchard at Cullinan during the 2009/2010 growing season in comparison to the four stage crop coefficient curve published in FAO-56 for stone fruit orchards..... 188

Figure 7.7 Comparison between observed and estimated crop coefficients (K_c) using a pecan-specific single crop coefficient approach with (A, B) reference crop coefficients from New Mexico and (C, D) reference crop coefficients adjusted for climatic conditions at the study site, during the 2010/2011 and 2011/2012 seasons. 189

Figure 7.8 Six stage crop coefficient (K_c) curves for a well-managed, mature pecan orchard at Cullinan and New Mexico. 190

Figure 7.9 Reference crop coefficients (K_{c-ref}) adjusted for specific climatic conditions using Growing Degree Days (GDD) for some of the pecan growing regions



in South Africa namely, Cullinan, Prieska and Upington using a simple polynomial function developed by Sammis *et al.* (2004). 191

Figure 7.10 Comparison between actual and estimated crop evapotranspiration (ET) using a pecan specific single crop coefficient approach with (A, B) reference crop coefficients (K_{c-ref}) from New Mexico and (C, D) reference crop coefficients adjusted (length of the various growth stages) for climatic conditions at the study site, during the 2010/2011 and 2011/2012 seasons. 193

Figure 7.11 Time-average crop coefficient (K_c) curve for macadamias derived from field measurements during the 2010/2011 growing season at the White River experimental site compared to K_c values for citrus derived from time-average K_c values published in FAO-56. 195

Figure 7.12 Monthly crop coefficients (K_c) for macadamias determined using the time-average K_c curve obtained from field measurements during the 2010/2011 growing season at the White River study site, compared to those of citrus developed from published values in FAO-56. 196

Figure 7.13 Comparison between actual evapotranspiration (ET) of macadamias during the 2011/2012 growing season and ET estimated using the generic FAO-56 model with (A) K_c values for citrus and (B) macadamia-specific K_c values. 197

LIST OF TABLES

Table 2.1 Top tree nut crops produced in the world, their total supply value and the world leading producing countries (INC, 2015b; INC, 2015c).....	9
Table 2.2 Hydraulic flow resistance for various fruit tree species (Larsen <i>et al.</i> 1989; Lloyd <i>et al.</i> 1991).....	18
Table 2.3 Measured water use published for tree nut crops under various conditions of climate and irrigation systems.	36
Table 2.4 Values for C_n and C_d coefficients for calculation of reference ET (Pereira <i>et al.</i> 2015).	41
Table 2.5 Single crop coefficients (K_c) during different growth stages, for well-managed fruit tree crops in sub-humid climates (Allen <i>et al.</i> 1998).....	42
Table 3.1 Details of the trees selected for sap flow measurements in the pecan and macadamia orchards.....	73
Table 5.1 Input parameters used to model hourly and daily values of fractional photosynthetically active radiation intercepted by a closed-canopy pecan orchard in Cullinan, an open-canopy pecan orchard at Hatfield and an open-canopy macadamia orchard at White River.....	110
Table 5.2 Input parameters selected for sensitivity analyses in the different approaches to model daily transpiration.....	114
Table 5.3 Regressions of the ratio of intercepted radiation and canopy conductance versus vapour pressure deficit. The intercept (a) and slope (b) of the linear regression equations are also shown, including the empirical coefficient D_o calculated as the ratio a/b, which relates the response of stomatal closure to vapour pressure deficit. The root mean square error (RMSE) of the simulated transpiration versus the observed one (mm day^{-1}) is also presented.....	128

Table 5.4 Sensitivity analysis results on seasonal transpiration predicted using the FAO-56 and canopy conductance models.....	134
Table 6.1 Soil and crop parameters used for parameterization of the FAO-56 dual crop coefficient model to estimate soil evaporation in the different experimental orchards.	144
Table 6.2 Input parameters selected for sensitivity analyses in the FAO-56 dual crop coefficient approach to model daily soil evaporation.	145
Table 6.3 Description of orchard characteristics and soil evaporation modelling scenarios simulated.....	147
Table 6.4 Sensitivity analysis results on seasonal soil evaporation predicted using the FAO-56 dual K_c model.....	160
Table 7.1 Measured monthly crop coefficients for the reference pecan orchard (K_{C-ref}) given by Samani <i>et al.</i> (2011) for New Mexico conditions, which have been offset by 6 months to adjust for the seasons in the southern hemisphere.....	175
Table 7.2 Pecan growth stages throughout the season when the trees are in leaf as defined by Herrera (1990) and Wells (2007). Values of K_{C-ref} throughout the growing season were published by Samani <i>et al.</i> (2011).	176
Table 7.3 Yield, seasonal water use (ET) and water use efficiency (WUE) of bearing pecan and macadamia trees under non-limiting water supply conditions.	186

LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

AWS	Automatic weather station
CI	Confidence interval
CHPM	Compensation heat-pulse method
E	East
EBR	Energy balance ratio
F	Furrow
G	Grass
HRM	Heat-ratio method
ID	In between drippers
IRGA	Infrared gas analyser
MAPD	Mean absolute percent difference
OPEC	Open Path Eddy Covariance
PAR	Photosynthetically active radiation
R	Ridge
R ²	Coefficient of determination
RMSE	Root mean square error
SAS	Statistical Analysis Software
SI	Sensitivity index
TDR	Time-Domain Reflectometer
UD	Under the dripper
W	West
WRC	Water Research Commission
WUE	Water use efficiency

SYMBOLS

A _c	Available energy input above the canopy
A _s	Available energy input above the soil surface
A	Net CO ₂ assimilation
c _p	Specific heat of air at constant pressure
c _g	Specific gravity of wood

C_d	Specific heat capacity of dry wood
C_w	Specific heat capacity of water
C_f	Specific heat capacity of fresh wood
C_s	Specific heat capacity of sap
C_a	Ambient CO ₂ concentration
C_P	Canopy porosity
CR	Capillary rise
DP	Deep percolation
D_{ax}	Axial thermal diffusivity of the sapwood
D_e	Cumulative depth of evaporation from the top soil layer
e_a	Actual vapour pressure
e_s	Saturation vapour pressure
ET_o	Reference evapotranspiration
ET	Crop evapotranspiration
E_s	Soil evaporation
E_x	Spacing between rows
E_y	Distance between trees within a row
$f_{c\ eff}$	Effective fractional cover
$f_{,h}$	Fraction of the orchard floor that is shaded at any given hour
$f_{b,h}$	Beam radiation interception
F_r	Degree of stomatal control on transpiration
$f_{c\ eff}$	Effective fractional canopy cover
f_{IPAR}	Fractional interception of photosynthetically active radiation
f_d	Diffuse radiation interception fraction of the orchard
g_a	Aerodynamic conductance
g_s	Leaf stomatal conductance
g_c	Canopy conductance
G	Soil heat flux
GDD	Growing Degree Day
h	Mean plant height
H	Sensible heat flux density
I	Irrigation
K_{ax}	Axial thermal heat conductivity

K_c	Crop coefficient
$K_{c \text{ mid}}$	Crop coefficient during the mid-season under partial ground cover
$K_{c \text{ full}}$	Crop coefficient during the mid-season under full ground cover
K_{cb}	Basal crop coefficient
K_d	Density coefficient
K_e	Soil evaporation coefficient
K_r	Dimensionless evaporation reduction coefficient
K_t	Transpiration crop coefficient
K_w	Thermal conductivity of water
LAI	Leaf area index
LE	Latent heat flux
L_x	Maximum length of the shadow cast by the trees in the direction perpendicular to the row
L_y	Maximum length of the shadow cast by the trees in the direction along the row
MC	Water content of the sapwood
MC_{FSP}	Water content at the fibre saturation point
M_L	Empirical parameter imposing an upper limit on transpiration
P	Precipitation
P_a	Atmospheric pressure
Q	Internal heat
Q_{FD}	Quantum flux density
r_s^c	Bulk stomatal resistances of the canopy
r_a^c	Boundary layer resistance
r_a^s	Aerodynamic resistance from soil to canopy
r_a^a	Aerodynamic resistance from canopy to reference height
r_s^s	Soil surface resistance
RH	Relative humidity
RO	Surface runoff
R_n	Net radiation
R_s	Total daily solar radiation
s	Slope of the terrain

SI	Sensitivity index
T	Whole-tree transpiration
T_l	Leaf temperature
T_c	Canopy transpiration
T_a	Air temperature
t	Time
t_{sr}	Time of solar rise
t_{ss}	Time of solar sunset
T_b	Base temperature
u_2	Wind speed
V_h	Heat pulse velocity
V_c	Corrected heat pulse velocity
V	Volume of the wood sample
VPD	Air vapour pressure deficit
VPD_l	Leaf-to-air vapour pressure deficit calculated at leaf temperature
w_f	Fresh weight of the wood sample
w_d	Oven-dried weight of the wood sample
W_x	Canopy width
W_y	Canopy depth
x	Distance
Δ	Slope of the saturation vapour pressure-temperature curve
ΔS	Changes in soil water storage
Ω	Decoupling coefficient
β	Bowen ratio
γ	Psychometric constant
ΔT_a	Air temperature difference
ΔT	Temperature difference relative to ambient
Δe_a	Air vapour pressure difference
w'	Vertical wind speed
q'	Vertical humidity
ψ	Leaf water potential
λ	Constant of latent heat of vaporization

α	Leaf absorptivity coefficient for PAR
ρ	Density of water
θ	Zenith angle of the sun
ρ_a	Air density
ρ_c	Volumetric heat capacity
ρ_w	Density of fresh wood
ρ_s	Density of sap
ρ_{cw}	Cell wall density
ρ_d	Density of dry wood
θ	Volumetric soil water content
λ	Thermal conductivity
T	Percentile
T_{sg}	Global solar radiation transmittance
T_{PAR}	PAR transmittance
T_b	Orchard-based beam transmittance
T_d	Effective orchard diffuse transmittance
θ_s	Sun azimuth
θ_R	Row azimuth
δ_e	Above-canopy atmospheric humidity deficit

CHAPTER 1: GENERAL INTRODUCTION

1.1 BACKGROUND AND RELEVANCE OF THE STUDY

Tree nut crops can be classified according to their growth habit as deciduous (which are typically adapted to temperate climates and lose their leaves during the winter period) or evergreen species (which are adapted to tropical and subtropical climates, with leaves remaining on the tree throughout the year). Deciduous species form the largest group of tree nut crops and these include almonds, walnuts, hazelnuts, pistachios and pecans, while cashews and macadamias are categorized as evergreen species (Andersen, 1994; Stephenson and Trochoulias, 1994; Sánchez and Webster, 2002). These two categories of tree nut crops differ in morphological, physiological and anatomical characteristics, which may result in differences in whole-tree transpiration (T), with consequent impact on irrigation scheduling and irrigation water management (Sobrado, 1986; Sobrado, 1991; Arora *et al.* 1992; Eamus, 1999; Walters and Reich, 1999).

Appropriate quantification of crop water use or evapotranspiration (ET, composed of soil evaporation (E_s) and whole-tree T) is crucial in fruit tree orchards to ensure adequate water supply for optimal fruit production in order to maximise orchard profitability. A shortage or excess of water are both detrimental for fruit trees. Soil water deficit may reduce vegetative growth, flower bud development, fruit set, fruit growth and quality, root growth, nutrient uptake and reserve storage (Kuroda *et al.* 1985; Lakso, 1985; Mirás-Avalos *et al.* 2013). Whilst excessive water supply often results in limited water and air movement in the soil, causing reduced nutrient and water uptake by roots, as well as retarded root growth, with a consequent increase in stomatal resistance, a decline of root hydraulic conductivity and photosynthesis (Gil *et al.* 2007; Morales-Olmedo *et al.* 2015) and increased disease incidence. Accurate quantification of ET of fruit tree crops has been included amongst the key solutions to reduce water scarcity in South Africa, through the reduction of over-irrigation often practiced by growers (Jarmain *et al.* 2014). This will ultimately contribute to increased water savings by maximizing crop water use efficiency. With increased levels of water scarcity in South Africa, the government has decided to take measures to ensure that

appropriate allocation and usage of the available water resources occurs in the various sectors, of which agriculture is currently the biggest water user, with 60% of the total fresh available water being allocated to irrigation (DWA, 2013). Such measures include issuing appropriate water licences to growers based on specific crop water needs. It was in this context that the Water Research Commission (WRC) of South Africa solicited, funded and managed a project (WRC Report No. 1770/2/14) to quantify ET of the main fruit tree species in South Africa, which included pecans and macadamias (Gush and Taylor, 2014).

There are various measurement methods available to quantify ET of fruit tree crops, which vary in their degree of complexity, accuracy and affordability. Weighing lysimeters are considered the gold standard for estimating water use, but they can be expensive and impractical, whilst micrometeorological methods such as the energy balance, eddy covariance and surface renewal are expensive to acquire and demanding in terms of the accuracy of measurements and operation skills (Rana and Katerji, 2000; Allen *et al.* 2011a). Crop ET measurements using any of the methods mentioned become tedious, very expensive and too time-consuming when dealing with fruit tree species due to their large size and long growing cycle relative to annual crops. As a result, crop modelling has been extensively used to simulate ET of fruit tree orchards under a wide range of conditions, including climate and orchard management practices. In order to develop new modelling approaches, or select an appropriate existing approach to estimate crop ET, or its partitioning into E_s and T , an understanding of the regulation of plant water relations is necessary. Whilst a few studies have reported the effect of selected environmental variables on yield and growth of macadamias (Stephenson and Gallagher 1989; Trochoulis and Johns, 1992), none of them describe their relation to crop ET or T . Studies on water use of pecans have mostly demonstrated the effect of canopy cover and atmospheric evaporative demand on crop coefficients and ET, with none of them showing the effect of individual atmospheric variables on crop ET or T , thus limiting the identification of the most dominant variable(s) controlling canopy conductance and T . Therefore, detailed studies to understand the environmental control of water use in pecan and macadamia trees are still lacking.

The quantification of pecan ET has been largely restricted to several parts of the United States of America, which is the top pecan producing country in the world (INC, 2015b; INC, 2015c). Studies conducted in New Mexico report that seasonal ET of mature pecan orchards varies between 1095 to 1307 mm (Miyamoto, 1983; Sammis *et al.* 2004; Samani *et al.* 2009). This large variation in reported ET for mature pecans is mostly attributed to differences in tree spacing and pruning strategies, which result in variations of fractional canopy cover. Whilst a number of studies have documented pecan ET, there is only one report on ET of macadamias growing in lysimeters in Queensland, Australia, where mean daily ET of a 12-year-old tree was 75 L day⁻¹ (Stephenson *et al.* 2003). The pecan and macadamia industries in South Africa are rapidly expanding (currently producing at least 5 918 t of pecan kernel and 24 230 t of macadamia kernel; INC, 2015a; SAMAC, 2017a) to meet the market demand. The latest statistics indicate that, there is at least 20 000 ha planted with pecan trees and 28 000 ha planted with macadamia trees, registering a yearly expansion of 2 to 3% for pecans and 8% for macadamias (A. Coetzee, personal communication, 24 August, 2017; SAMAC, 2017b). As the production area increases, the demand for water also increases, and thus, the appropriate quantification of crop ET is necessary for optimum irrigation water management and planning. There is presently a lack of knowledge of ET of pecan and macadamia orchards under South African conditions. In addition, data on T for these orchards is completely nonexistent worldwide. Water resource management and planning for these orchards based on the findings obtained from other parts of the world or on other crops could, therefore, lead to incorrect water supply estimates, resulting in poor production and orchard profitability (de Villiers and Joubert, 2003; de Villiers and Joubert, 2008).

Site-specific crop ET, T and E_s, under conditions of adequate soil water, is often obtained using modelling approaches, starting from simple, empirical approaches to the more complex, mechanistic approaches (Rana and Katerji, 2000; Egea *et al.* 2011; Dong *et al.* 2014; Kool *et al.* 2014; Verhoef and Egea, 2014; Subedi and Chávez, 2015). Simple, empirical approaches are more easily parameterized, but they often have restricted validity for spatial applications and short-time step simulations, thus limiting their applicability to irrigation planning only. Mechanistic approaches, on the other hand, can be more widely transferred and used for real-time simulations, which are important for accurate irrigation scheduling, but the required input parameters

need to be correctly determined (Leenhardt *et al.* 1995). Several simple modelling procedures have been developed to adjust crop coefficients of pecans to specific climatic conditions and orchard management practices, but they have not been evaluated in production regions other than where they were developed, which may differ in both climate and irrigation system employed (Miyamoto, 1983; Allen *et al.* 1998; Sammis *et al.* 2004; Wang *et al.* 2007; Allen and Pereira, 2009; Samani *et al.* 2011). 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. Mechanistic models, which often predict the component of T separately from E_s taking into account stomatal regulation, have only been parameterized for selected fruit tree species, which did not include pecans and macadamias (Allen and Pereira, 2009; Villalobos *et al.* 2013; Taylor *et al.* 2015).

1.2 MAIN HYPOTHESES

1. As with most tall horticultural crops, T of pecans and macadamias would be well-coupled to the atmosphere. The high degree of T coupling was expected to influence the manner in which these tree nut crops lose water through the process of T. Transpiration would therefore be primarily driven by VPD and regulated by stomata;
2. Due to the presence of a strong stomatal control of T in pecans and macadamias, it was expected that daily T of these tree nut species would be more accurately estimated using a canopy conductance approach than using a crop coefficient approach, which assumes demand limited T;
3. Daily E_s beneath the canopy of pecan and macadamia orchards, on the other hand, was expected to be accurately predicted using appropriate measurements of changes in canopy size, wetted fractions of the soil surface by irrigation and a detailed record of irrigation and rainfall events through the application of a mechanistic E_s model;
4. Crop ET and crop coefficients of pecans were expected to be more variable compared to that of macadamias, as a result of more profound changes in canopy size. Consequently, monthly crop ET of pecans would be accurately predicted with a crop-specific modelling approach, while a generic modelling approach would be accurate enough for macadamias.

1.3 AIM OF THE STUDY

The aim of this study was to investigate the regulation of T and E_s in pecan and macadamia orchards in order to identify the most suitable crop modelling approaches to estimate the water use of these crops, for improved irrigation scheduling and irrigation water management of orchards growing under a range of climates and management practices.

1.4 OBJECTIVES

In order to meet the aim of the study, the following specific objectives were formulated:

1. Measure the unstressed ET and T of pecan and macadamia orchards, whilst monitoring environmental variables and tree canopy development changes throughout the growing season;
2. Determine the decoupling coefficient of irrigated pecan and macadamia trees grown under field conditions;
3. Evaluate the response of T of these crops to different individual environmental variables using a segmented quantile regression approach;
4. Study the integrated effect of the most controlling atmospheric variables on T ;
5. Parameterize and validate a simple radiation interception model to estimate hourly and daily fractional interception of photosynthetically active radiation by pecan and macadamia trees;
6. Compare the performance of a canopy conductance model approach to a crop coefficient model approach for model parameterization and validation to estimate daily T of unstressed pecans and macadamias trees;
7. Characterize E_s variability in pecan and macadamia orchards;
8. Parameterize and validate the FAO-56 dual crop coefficient model for the estimation of daily E_s in these orchard crops;
9. Improve and validate existing single crop coefficient modelling approaches for the estimation of unstressed monthly ET of pecans and macadamias.

1.5 THESIS OUTLINE

A review of the available literature on the regulation of water use, measurement techniques and modelling approaches for the quantification of water use of fruit tree orchards is presented in Chapter 2. Knowledge gaps are identified and contributions to the existing knowledge by the current study are proposed. Chapter 3 provides general detail of where and how the study was conducted, while specific details of the study methodology are presented in each respective results and discussion chapter. Chapter 4 provides a detailed assessment of the regulation of T per unit leaf area in pecan and macadamia trees to help with the selection of an appropriate modelling approach for estimation of daily T of these crops. Chapter 5 compares the performance of two distinct modelling approaches (a canopy conductance against a crop coefficient modelling approach) to estimate daily T of pecans and macadamias under non-limited soil water supply. Chapter 6 presents a detailed characterization of the process of E_s beneath the canopy of pecan and macadamia trees and its daily estimation for the entire experimental period using a mechanistic E_s model, which was successfully parameterized and validated using measured data in this study. An evaluation of different single crop coefficient modelling approaches to estimate monthly ET of pecans and macadamias is presented in Chapter 7, which will aid with more appropriate irrigation planning and water resource management of these orchards. Chapter 8 provides general conclusions for the study and recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 PRODUCTION OF TREE NUT CROPS

The major tree nut crops produced around the world include almonds (*Prunus dulcis*), pistachios (*Pistacia vera*), cashews (*Anacardium occidentale*), hazelnuts (*Corylus avellana*), walnuts (*Juglans* spp.), pecans (*Carya illinoensis*) and macadamias (*Macadamia integrifolia*, *Macadamia tetraphylla*) (INC, 2015c). The world total production of tree nuts has increased significantly (approximately 60%) in the past 12 years (INC, 2015b). The interest in their cultivation is vindicated by its high nutritional value, as they are rich in protein and fat, as well as minerals and some vitamins (Jaynes, 1969). They also contain a considerable amount of phytochemicals, including carotenoids, phenolic acids, phytosterols and polyphenolic compounds, all of which contributing significantly to human nutrition (Bolling *et al.* 2011).

Tree nuts are produced by various countries in the world. Figure 2.1 illustrates the top 10 world producing countries, of which USA is the biggest producer (1 531 930 t kernel), followed by Turkey (579 755 t kernel) and China (221 573 t kernel) (INC, 2015c). The top three producing countries for each main tree nut crop is illustrated in Table 2.1 (INC, 2015b; INC, 2015c). South Africa is the leading producer of macadamias (total production area of 28 000 ha; SAMAC, 2017b) and the third largest producer of pecans in the world (total production area of 20 000 ha; A. Coetzee, personal communication, August 24, 2017). The pecan and macadamia industries in South Africa are rapidly expanding, with production of these crops increasing considerably over the past 10 years (INC, 2015b), with a total current production exceeding 5 918 t of kernel for pecans and 24 230 t of kernel for macadamias (INC, 2015a; SAMAC, 2017a). Moreover, South Africa has also become the leading exporter of macadamias and the fourth largest exporter of pecans in the world (NAMC and DAFF, 2013; INC, 2015b). South Africa exports approximately 32% of the total world's macadamia nut production (INC, 2015b), contributing approximately R600 million to the total gross value of agricultural production over a 10-year period (DAFF, 2014). Although the export of pecans only accounts for 5% of the global share, it is important to note that almost 100% of the total production of pecan nuts in South Africa is

exported, contributing to almost R1 300 million over a five-year period (NAMC and DAFF, 2013).

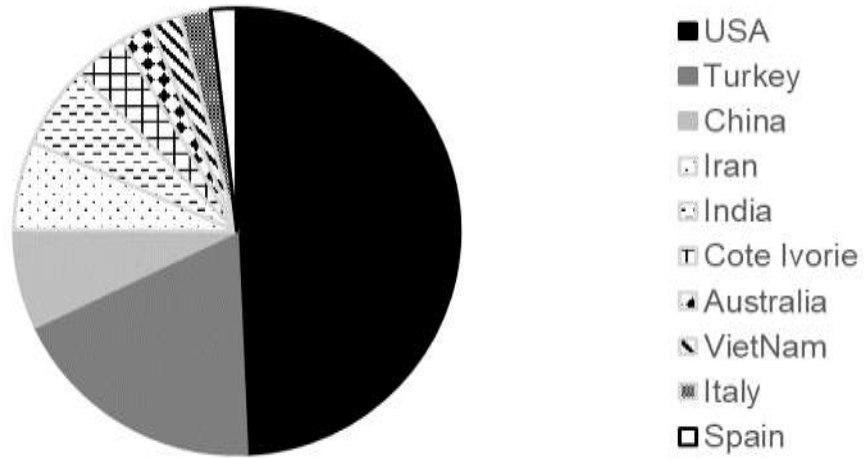


Figure 2.1 Top ten world-producing countries of tree nut crops (INC, 2015c).

Table 2.1 Top tree nut crops produced in the world, their total supply value and the world leading producing countries (INC, 2015b; INC, 2015c).

Tree nut crop	Total production in 2014 (Un-shelled, 10 ³ t)	Total supply value in 2014 (Shelled, Million \$)	Top three producers (1 st , 2 nd , 3 rd)
Almonds	1185	8.3	USA, Australia, Spain
Pistachios	702	7.0	USA, Iran, Turkey
Cashews	693	4.7	West Africa, India, Viet Nam
Hazelnuts	372	3.7	Turkey, Italy, USA
Walnuts	721	6.4	USA, China, Iran
Pecans	119	1.5	USA, Mexico, South Africa
Macadamias	49	0.6	South Africa, Australia, Kenya
Brazil nuts	28	0.2	Bolivia, Peru, Brazil
Pine nuts	44	1.1	China, Korea DPR, Afghanistan

The main growing areas for macadamias in South Africa are the subtropical areas of the Lowveld, Levubu and KwaZulu-Natal, where the climate is warm to hot, with very light or minimum frosts (DAFF, 2006; du Preez, 2015). Pecans, on the other hand, are commonly found in climatic areas with short, cold winters and long, very hot summers, such as the Southern Lowveld area, White River, Tzaneen, the Vaalharts Irrigation Scheme, the Middleveld around Pretoria and some parts along the Orange River such as Hartswater and Prieska (de Villers and Joubert, 2008). These regions are generally characterized by lithic soils, which are well-drained, medium in texture, with convex crests, steep slopes and rocky material. Other groups of soils occurring in small percentages include oxidic (colored with red or yellow oxides of iron) and humic soils (with a remarkable accumulation of humus) (Fey, 2010).

Macadamias are cultivated in more humid rainfall areas (with 800 – 900 mm of annual rainfall), while pecans are produced in regions with low temperatures and frost occurrence during winter when the trees are dormant. As pecans are highly sensitive to scab development, these areas are relatively low in humidity and rainfall (200 – 800 mm of annual rainfall). Besides the occurrence of low rainfall, these regions including those for macadamia production, are predominantly characterized by arid to semi-arid climatic conditions, where rainfall is poorly distributed with prolonged dry spells and torrential rainfall events, which in either case can be detrimental for crop productivity. Consequently, irrigation is vital to meet crop water requirements, particularly when the atmospheric evaporative demand exceeds the available rainfall, which is the case for all these regions in which pecans and macadamias are produced (with water deficits between 16 and 80%).

2.2 MORPHOLOGICAL, PHYSIOLOGICAL AND ANATOMICAL CHARACTERISTICS OF DECIDUOUS AND EVERGREEN TREE NUT CROPS IN RELATION TO CROP WATER USE

Tree nut crops can be classified according to their growth habit as deciduous or evergreen species. Deciduous species are adapted to temperate climates and shoot growth usually begins in spring, continues for a finite period of time during the warm and wet period of the year and then slows down and stops, usually for the rest of the year (two to four months, during winter when the environment is cold and dry; Eamus,

1999). They form the largest group of tree nut crops which include almonds, walnuts, hazelnuts, pistachios and pecans, while cashews and macadamias are categorized as evergreen species (Andersen, 1994; Sánchez and Webster, 2002). In contrast to deciduous species, evergreen species are adapted to tropical and subtropical climates and their leaves remain on the trees continuously throughout the year maintaining regular T rates (Stephenson and Trochoulis, 1994). Knowledge of morphological, physiological and anatomical characteristics of crops is important to understand how different species respond to changes in environmental conditions (Sobrado, 1986; Sobrado, 1991; Arora *et al.* 1992; Eamus, 1999; Walters and Reich, 1999). For instance, it has been documented that leaves of evergreen tree species have longer life-span and smaller fluctuations of leaf water potentials, turgor pressure and leaf water content per unit of dry mass throughout the season, than leaves from deciduous species (Sobrado, 1986; Sobrado, 1991). As a result, evergreen species are generally considered more drought tolerant than deciduous species. Leaves of evergreen species are usually thick and sclerophyllous or xeromorphous (Sobrado, 1986; Schaffer *et al.* 1994; Syvertsen *et al.* 1995; Chartzoulakis *et al.* 1999; Carr, 2012a; Carr, 2012b), whilst deciduous species have thin, mesophytic leaves (Sobrado, 1986; Andersen, 1994; Qi *et al.* 2003).

Deciduous and evergreen tree species have different mechanisms to function in water-limited environments (Arora *et al.* 1992), which is probably attributable to their varying growth habits. Deciduous tree species escape from cold and dry environments through vegetative dormancy during winter (Vilagrosa *et al.* 2012). Several factors affect the length of the growth and dormancy periods, including climatic conditions, tree age and bud structure in relation to shoot position (Hunter and Lechowicz, 1992; Campoy *et al.* 2011). Evergreen species, on the other hand, are considered to be drought avoidant (Vilagrosa *et al.* 2012), which is, in some instances, attributed to the existence of a more efficient root system that allows water extraction from deeper soil layers or by having mechanisms which allow the conservation of water within the tree (Sobrado, 1986). Tree species adapted to the tropics (like many evergreen species) usually have higher leaf-specific conductivity rates (an index that measures the ability of the stem to supply water to leaves) than species adapted to temperate climatic conditions (most deciduous trees) (Eamus, 1999). As a result, they often require a

smaller gradient of water potential between leaf and soil to maintain the same T rates as temperate species (Eamus, 1999).

2.3 FACTORS AFFECTING GROWTH, PHYSIOLOGY AND CROP WATER USE

2.3.1 Environmental conditions

Changes in environmental variables have a direct influence on atmospheric evaporative demand, which impacts crop ET, through both T and E_s . The manner in which T responds to changing environmental conditions differs between temperate deciduous species and tropical/subtropical evergreen species. Net CO₂ assimilation (A) increased with an increase in incident solar radiation until light saturation values between 1500 and 1800 $\mu\text{mol quanta m}^{-2} \text{s}^{-1}$ were reached for leaves of deciduous tree crops such as almonds, chestnuts and pecans (Andersen, 1994). In evergreen tree crops, the light saturation values were lower (up to 1200 – 1300 $\mu\text{mol quanta m}^{-2} \text{s}^{-1}$ for macadamias, Stephenson and Trochoulis, 1994; 350 – 400 $\mu\text{mol quanta m}^{-2} \text{s}^{-1}$ for mangoes, Schaffer *et al.* 1994; 300 – 600 $\mu\text{mol quanta m}^{-2} \text{s}^{-1}$ for coffee, Rena *et al.* 1994). This suggests that T in deciduous species may respond more positively to increased levels of incident solar radiation than in evergreen species. Thus, under conditions of high atmospheric evaporative demand (which is often proportional to increased incident solar radiation), evergreen species are more likely to exhibit stronger stomatal control over T to avoid possible environmental stress caused by drought or harsh atmospheric conditions.

Based on studies conducted on selected fruit tree species (almond, apple, fig, grape, olive, peach, pear and macadamia), deciduous species generally showed a sharper decrease in leaf stomatal conductance (g_s) with increased leaf to air vapour pressure deficits (VPD) in comparison to evergreen species (Lloyd *et al.* 1991; Higgins *et al.* 1992; Andersen, 1994). This often resulted in a higher VPD threshold for the maximum increase in T in deciduous species (VPD = 1.5 to 2.5 kPa) in comparison to evergreen species (1.0 to 1.5 kPa) (Higgins *et al.* 1992). In other words, T of evergreen species, such as olives and macadamias, is reduced through stomatal closure at lower VPDs in comparison to deciduous species, which is often explained by the presence of several morphological and physiological attributes in the evergreen species, which

contribute to tree survival during extended periods of stress (Andersen, 1994; Stephenson and Trochoulis, 1994). There are no studies reporting the environmental regulation of T in pecan trees. The only study reporting the environmental regulation of T in macadamia trees was conducted under controlled incident solar radiation using a shade net structure (Lloyd *et al.* 1991), and therefore, results might differ when compared to field-grown trees.

Soil water deficits significantly affect plant water relations, and overall crop productivity, by lowering the relative water content within the plant, leaf water potential, osmotic potential, pressure potential and T rates (Farooq *et al.* 2012). Reductions in g_s , sap flow rates and crop ET were observed in a number of fruit tree species due to soil water deficits (Torrecillas *et al.* 2000; Girona *et al.* 2002; Testi *et al.* 2004). In order to minimize the effect of drought, plants rely on adaptive strategies which are based on a number of morpho-anatomical traits expressed in different organs. In tree species these strategies may include the presence of leaves with xeromorphic traits, leaf shading (in the case of deciduous species), a decrease in leaf number and size, all of which contribute to minimizing T under drought conditions (de Micco and Aronne, 2012). Some tree species also have adaptive traits regulating the transport of water from roots to leaves, in which xylem hydraulic conductivity and xylem cavitation are the most important (de Micco and Aronne, 2012). Xylem cavitation may occur in roots, trunks and twigs of tree species when air enters functional conduits through pit membranes, resulting in a loss of xylem hydraulic conductance due to vapour and/or air filled embolized conduits (Sperry *et al.* 1993, Sperry and Saliendra, 1994). According to Sperry (2000), plant vulnerability to xylem cavitation is positively correlated to its level of drought adaptation, meaning that species which are more adapted to well-watered habitats are more susceptible to cavitation than those adapted to drier environments. This explains why drought tolerant fruit tree species, such as olives and citrus, have adaptation mechanisms to prevent the occurrence of xylem embolism and cavitation through stomatal regulation (Poggi *et al.* 2007; Ennajeh *et al.* 2008), resulting in a more gradual use of soil water even under conditions of non-limited soil water supply (Sperry, 2000). Most water relation studies on fruit tree species have been conducted under water stress conditions (Stephenson and Gallagher, 1989; Torrecillas *et al.* 2000; Girona *et al.* 2002; Testi *et al.* 2004). The water relations of fruit tree species grown under non-limiting soil water conditions has

yet to be studied, which has resulted in a lack of information on maximum crop responses to changes in atmospheric conditions and water-saving mechanisms in the absence of any crop water stress.

Elevated air temperatures (above 28 to 30 °C) restrict physiological processes and therefore growth of some deciduous tree nut crops, such as pistachio and walnut, but similar constraints have not been found for pecans (Andersen, 1994). Macadamia trees have a narrower preferable temperature range (20 to 25 °C) for optimum growth, and they are likely to be sensitive to extreme temperatures beyond this range, causing chlorosis of new leaves, inhibition and delayed production of summer growth flushes, as well as reduced yield and poor kernel quality (Stephenson and Trochoulias, 1994). Variations in air temperatures will also influence the length of the growing season of tree nut crops, particularly for temperate, deciduous species. Temperate crops require a distinct cold period during winter dormancy for optimum growth in spring (with temperatures falling below 1.2 and above -15 °C, Jackson, 1986; Mehlenbacher, 1991; Sparks, 1993; Burghardt and Riederer, 2008). The amount of chill accumulation in temperate deciduous crops will determine their heating requirements for budbreak in spring, as seen in pecans and peaches (Scalabrelli and Couvillon, 1986; Sparks, 1993). Thus, the effect of air temperatures on physiological processes, growth and length of the growing season may have an impact in the regulation of T. To date there are no studies reporting the effect of elevated air temperatures (above the optimum for crop growth) on T for fruit tree species.

2.3.2 Boundary layer and physiological conductances

Orchard crops, like most forest species, tend to be aerodynamically extremely rough, which results in greater boundary layer conductance (100 to 300 mm s⁻¹) as compared to field crops (Jones *et al.* 1985). Consequently, orchard crops tend to be closely-coupled to the environment, with T being much more sensitive to changes in the total leaf conductance than in many other crops (Figure 2.2).

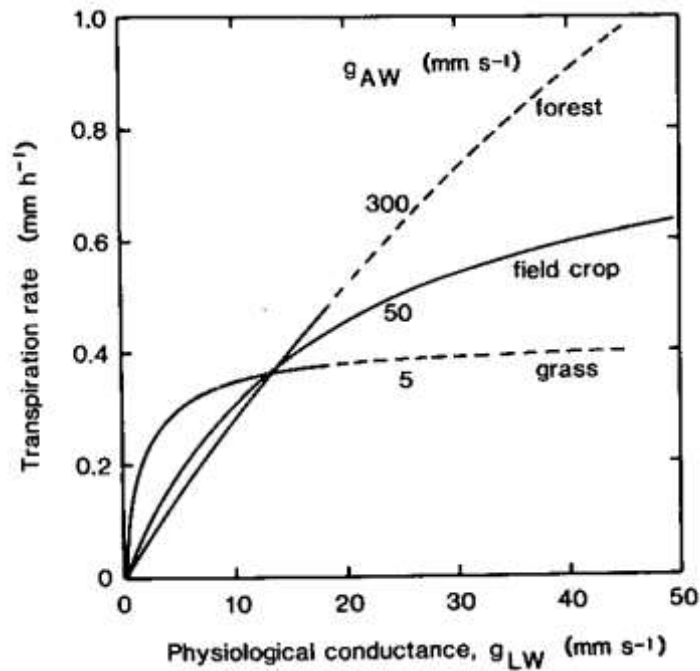


Figure 2.2 Effect of changing physiological conductances on transpiration from different crops. Note the greater sensitivity of transpiration to physiological conductance in tall crops such as forests or orchards (Jones *et al.* 1985).

In well-coupled crops, T proceeds at a rate largely set by the saturation vapour pressure deficit of the bulk air (Jarvis, 1985), where coupling is determined using an empirical coefficient (Ω , called decoupling coefficient) expressing the relative sensitivity of T to a marginal change in stomatal conductance (Jarvis and McNaughton, 1986). However, this degree of coupling of T to the atmosphere varies among different species depending on the height and leaf dimensions of the crop, and even within the same crop it will fluctuate depending on whether the leaves are in a leaf chamber, a growth room or greenhouse, or out in the field (Jarvis, 1985; Jones *et al.* 1985). For instance, under field conditions a 5 m tall citrus orchard has a higher Ω factor (0.3) compared to a 15 m cherry orchard (0.1) (Jarvis, 1985). The lower the Ω factor the higher the sensitivity of T to changes in physiological and boundary layer conductances, or in other words, the more well-coupled the crop is to the atmosphere. There are only few studies reporting the Ω factor for selected fruit tree species (citrus, olives and cherries) growing under field conditions (Jarvis, 1985; Marin and Angelocci, 2011; Tognetti *et al.* 2012). Based on these studies, both evergreen species (citrus and olives) showed higher Ω factors (0.2 – 0.3) as compared to the deciduous species

cherry ($\Omega = 0.1$). It would, however, be unsubstantiated to relate the differences in the magnitude of Ω between these two groups of species to their varying growth habits, as the data used for comparison is clearly very limited. However, as Jarvis (1985) mentioned, both groups of fruit tree species can be categorized as well-coupled crops, in which T is strongly dependent on canopy conductance (g_c), regulated by VPD. There are currently no studies reporting the Ω factor for pecans and macadamias.

The stomatal component provides the dominant short-term physiological control of T , of which several factors play an important role, such as changes in environmental variables (wind speed, humidity, atmospheric CO_2 , solar irradiance, air temperature and the availability of water in the soil), the plant hormone abscisic acid (ABA) and internal CO_2 concentrations in the leaf (Jones *et al.* 1985; Hetherington and Woodward, 2003; Araújo *et al.* 2011; Rico *et al.* 2013; Schymanski and Or, 2015). Under conditions of dry air, high atmospheric CO_2 concentrations, low solar irradiance, low temperatures, water stress and increased levels of ABA in the plant, stomata tend to close to minimize the effect of a changing environment on T . This is an important mechanism to maintain favourable tissue water potential in severely desiccating environments (Jones *et al.* 1985; Bolling *et al.* 2011). By contrast, stomata opening is induced by high solar irradiance, high humidity and low CO_2 concentrations in the atmosphere and plant tissue (Rico *et al.* 2013). Low or sub-ambient CO_2 concentrations significantly increase stomatal density and the size of stomatal pores, thus resulting in higher stomatal conductance and increased T , exposing the plants to greater vulnerability to cavitation, as a result of increased vessel diameter and xylem specific conductivity (Rico *et al.* 2013).

The degree of stomatal control of leaf water status is highly variable among plant species, resulting in different responses between plants with anisohydric behaviour or isohydric behaviour. In anisohydric plants (e.g. sunflower, barley, almond and peach trees) daytime leaf water potential markedly decreases with an increase in atmospheric evaporative demand, and is lower in stressed than in well-watered plants, whilst plants with isohydric behaviour (e.g. maize, pea, poplar and sugarcane) have daytime leaf water potentials that are less sensitive to changes in atmospheric evaporative demand, and can be independent of soil water status (Tardieu and Simonneau, 1998). Isohydric behaviour may be present in evergreen fruit tree species

such as citrus, for example, in which the stomata usually reopen more slowly than stomata in several temperate tree species, with good stomatal control over leaf water potential under a range of atmospheric evaporative demand conditions. This enables its acclimation to both humid and arid environments without little difference in water use between the two environments (Jones *et al.* 1985).

In the long-term, canopy conductance (g_c) and therefore whole-tree T will be regulated by leaf area index (LAI), which is the total area of live leaves per unit ground surface (Granier *et al.* 2000; Bolling *et al.* 2011). An increase in LAI, however, does not necessarily mean an increase in g_c , due to the fact that as LAI increases, the proportion of shaded leaves, which have lower conductances, also increases. The contribution of shaded leaves in lowering the whole tree g_c is more pronounced in large canopies, as seen in tree canopies with LAI above $6.0 \text{ m}^2 \text{ m}^{-2}$ where T rates of both deciduous and evergreen forest species remained fairly constant (Granier *et al.* 2000). However, leaf area changes in smaller canopies (with LAI $< 6.0 \text{ m}^2 \text{ m}^{-2}$) have been found to be a major factor determining changes in g_c and T of fruit tree crops, particularly for deciduous species (Johnson *et al.* 2000; Williams and Ayars, 2005; Goodwin *et al.* 2006). Changes in leaf area also serve as a natural drought adaptation mechanism, because a reduction in leaf area equates to a reduction in water loss. Soil water and a favourable soil water potential are thereby maintained and the evaporating surface per unit cross-section of the hydraulic pathway within the soil-plant system is also decreased, thus minimizing the difference in water potentials between the leaf and soil in order to reduce the driving force for water flow (Jones *et al.* 1985). Understanding the role of stomatal conductance is therefore important when modelling crop T. Currently, there are no canopy stomatal conductance modelling approaches, which have been parameterized or validated for the estimation of T of pecans and macadamias.

2.3.3 Hydraulic flow resistances

The hydraulic system within the soil – plant – atmosphere acts as a true continuum, in which water will move from the soil into the plant and through the plant into the atmosphere in response to a water potential gradient (Arora *et al.* 1992). In a well-hydrated plant, the greatest hydraulic resistance is in the leaf, in both the leaf xylem,

as well as in the flow paths across the mesophyll to evaporation sites (Bolling *et al.* 2011). The degree of resistance to water flow will vary between different species of fruit trees, as well as within the same species, depending on the rootstock, the total length and density of roots in the soil, the occurrence of pests and diseases, and changes in soil conditions, such as temperature and waterlogging (Jones *et al.* 1985). Increased soil temperatures, waterlogging or soil water deficits increase the flow resistance, with consequent decreases in plant water use. An increase in soil water stress will lower leaf water potential, thus decreasing leaf conductance and accelerating stomatal closure as a result of an increase in xylem resistance to water flow in order to prevent cavitation (Jones *et al.* 1985; Nicolás *et al.* 2005; Bolling *et al.* 2011). Table 2.2 shows variations in hydraulic flow resistances among different fruit tree species. Typical evergreen species, such as olive, have higher hydraulic flow resistance compared to deciduous species, such as apple and peach, with the exception of the macadamia tree, which has the lowest value. Lloyd *et al.* (1991) attributed such unexpected low hydraulic flow resistance in macadamia trees to a distinct adaptive advantage these trees have during extensive dry periods. Larsen *et al.* (1989) related hydraulic flow resistance to T, indicating that trees such as apple, with low resistance values, will use large amounts of water for adequate crop production, although the high stomatal sensitivity may allow it to withstand drought via stomatal closure. While trees like olive, with high resistance, would produce adequately without using much water. The impact of low hydraulic flow resistance on T of macadamias is still unclear, as there is currently very little information reported on T and ET of this crop (Carr, 2012a).

Table 2.2 Hydraulic flow resistance for various fruit tree species (Larsen *et al.* 1989; Lloyd *et al.* 1991).

Species	Hydraulic flow resistance (MPa/(mmol H ₂ O m ⁻² s ⁻¹))
Macadamia	0.18
Apple	0.33
Peach	0.58
Grape	0.60
Olive	0.85

2.3.4 Orchard management practices

Adequate orchard management is very important to ensure good water supply, in order to meet crop ET demands and achieve optimum crop growth. There are several orchard management practices which affect the water requirements of fruit tree orchards. These include the choice of irrigation system, soil ground cover management strategy, pruning and training strategies, and planting density (Jones *et al.* 1985).

The type and strategy of irrigation system chosen affects crop ET due to differences in the wetted area, which has an impact on E_s losses (Fallahi *et al.* 2010). Irrigation with a drip system for instance, requires lower water application for optimum crop growth than sprinkler irrigation due to more localized irrigation applications, which result in lower E_s losses. As plant root systems adapt to existing water regimes in the soil, irrigation systems with more localized water applications, such as drip and trickle systems, will promote more root growth, confined to the wetted area, and as a result, they will be more efficient than irrigation systems with ample water supply (Jones *et al.* 1985). The presence of a ground cover, such as grass alleyways or grass buffers, can improve infiltration of water into the soil and reduce runoff, thus increasing the amount of soil available water for crop water use (Roper, 1992). The use of a soil mulch, such as clippings of cover crops, pruning material or grass left on the soil surface, can improve soil water conservation through minimization of E_s losses, soil structure, temperature moderation and soil fertility (Jones *et al.* 1985; Green and Watson, 1989; Roper, 1992; Allen *et al.* 1998; Tolk *et al.* 1999).

Practices such as pruning, tying-down and the use of precocious rootstocks also influence crop ET. These practices will contribute to reduced total leaf area and radiation interception, resulting in lower T rates (Jones *et al.* 1985). Closed-canopy pecan orchards are generally intensively pruned every year to improve radiation interception through the canopy, which may consequently result in significant variations of seasonal T.

Increased planting densities in orchards are generally associated with an increase in leaf area per m^2 and higher volumes of roots, which may result in higher crop ET.

However, studies conducted in different orchard crops showed higher root densities for trees planted with narrower spacing, but revealed contradictory results of the effect of plant densities on crop ET (Whitney *et al.* 1991). Most studies reporting measured ET of pecan orchards have been conducted under similar orchard management practices in New Mexico, where pecans are usually widely spaced (10 m x 10 m) and irrigated using flood irrigation (Miyamoto, 1983; Steinberg *et al.* 1990; Sammis *et al.* 2004).

2.4 MEASUREMENT OF CROP WATER USE

Several methods have been used to measure water use of fruit tree species, which vary in their degree of accuracy, complexity and affordability. According to Rana and Katerji (2000) and Allen *et al.* (2011a), these methods can be grouped into different categories based on their specific approaches to determine crop water use. These include hydrological approaches (lysimetry and soil water balance), micrometeorological approaches (energy balance and Bowen ratio, eddy covariance and surface renewal method), remote sensing (remote sensing energy balance and satellite-based crop ET using vegetation indexes from satellite images or aerial photography) and plant physiology approaches (sap flow/sap flux density methods and chamber systems). Most of these methods, such as the energy balance and micrometeorological methods, require expensive equipment and are demanding in terms of the accuracy of measurements and operation skills. Despite these limitations, it is very important to conduct crop water use measurements in order to characterize water use in orchard crops and identify the most relevant driving factors. This will enable analysis of irrigation efficiencies and scheduling, in addition to parameterization and validation of crop models for the estimation of crop water use. A brief review of the various methods is provided below.

2.4.1 Hydrological approaches

2.4.1.1 Lysimetry

A lysimeter is a terrain block (a monolith of soil or a disturbed soil sample) inserted in a container, in which measurements, such as weighing and chemical analysis on

drainage water, are carried out. There are two basic types of lysimeter: weighing lysimeters for determining water use and non-weighing lysimeters for chemical analysis on drainage water (Parisi *et al.* 2009). This review will focus on weighing lysimeters for measuring crop ET, T or E_s in agricultural production.

In weighing lysimetry systems, the crop ET, T or E_s is measured directly using a manual method with mechanical scales and counter-balanced scales, or automatically using a datalogger connected to digital load cells (Allen *et al.* 2011a). The advantages of this method are that the total crop ET, T or E_s is measured directly by the change of mass of an isolated soil volume. As a result, it does not require calibration and offers the opportunity to investigate a range of hydrological processes (Payero and Irmak, 2008). The main disadvantage is that the lysimeter rim can influence measurements, particularly in arid environments due to heating of the metallic rim by radiation, which results in micro-advection of sensible heat into the lysimeter canopy. The depth of the lysimeter can be a limitation to measure crop ET or T of tall crops, such as fruit trees, as it will not take into account the effect of the deeper water fluxes, such as capillary rise for instance, and they may not be portable, limiting their use to research stations (Rana and Katerji, 2000; Zapata and Martínez-Cob, 2002; Allen *et al.* 2011a). Moreover, as orchard crops are quite tall, both aerodynamic and radiative transfer to the lysimeter canopy are increased, resulting in increased ET and T from the lysimeter area (Allen *et al.* 2011a). Despite these limitations, weighing lysimeters provide good measurements of ET, T or E_s for fruit tree species, and is often considered the standard method for direct measurements, with application in the calibration of crop models and methods for estimation of T (Ferreira *et al.* 1996; Castel, 1997; Ayars *et al.* 2003; Payero and Irmak, 2008).

2.4.1.2 Soil water balance

Crop ET can also be determined using the soil water balance method, which consists of assessing the incoming and outgoing water fluxes into the crop root zone over time (Figure 2.3) (Allen *et al.* 1998). The inputs into the soil consist of irrigation (I) and precipitation (P), while the outputs are those components which lead to a reduction in soil water and include surface runoff (RO), deep percolation below the root system (DP) and crop ET (Palomo *et al.* 2002). In some cases, soil water might move upwards

by capillary rise (CR) from a shallow water table to the root zone, or horizontally by subsurface flow in to or out of the root zone and this is then considered an input to the system (Allen *et al.* 1998; David *et al.* 2007). Changes in soil water storage (ΔS) should also be considered. Thus, a more representative soil water balance equation includes the following components (Allen *et al.* 1998):

$$ET = P + I + CR - DP - RO \pm \Delta S \quad (2.1)$$

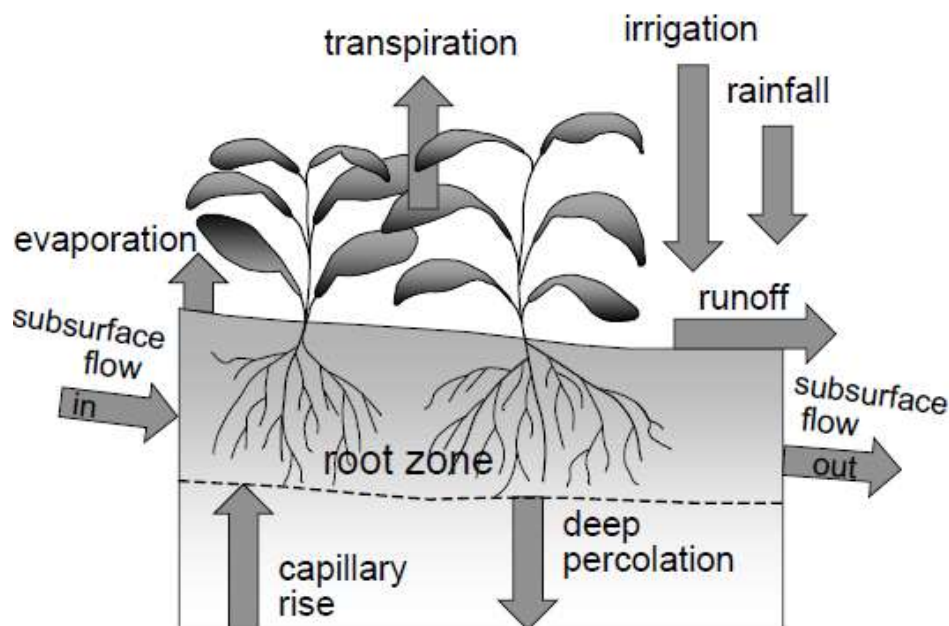


Figure 2.3 The components of a soil water balance system. The inputs to the system are rainfall, irrigation and the water brought by capillary rise from a ground water-table to the root zone, while the outputs are transpiration, soil evaporation, runoff and deep percolation. Changes in soil water content due to subsurface flow may contribute to the system as either an input or output (Allen *et al.* 1998).

When determining crop ET using the soil water balance method, components such as RO, DP, subsurface flow and water brought by CR are often ignored, due to the fact that they are difficult to quantify. The total amount of P is also more commonly used, instead of effective P that eliminates the amount of P lost through canopy interception (Goldhamer *et al.* 1993; Rana and Katerji, 2000). Ignoring such components often

results in inaccurate measurements of the crop ET (Rana and Katerji, 2000). Besides, this method has a low temporal resolution (a few days), requiring frequent monitoring of the equation components, thus making it laborious and time consuming, resulting in its limited use for irrigation scheduling purposes (Fernández and Moreno, 1999).

Considering all the limitations with the use of the soil water balance approach, proper precautions should be taken to increase the accuracy of crop ET estimations using this method, which include the use of appropriate parametric modelling to estimate deep fluxes (Allen *et al.* 2011a). When DP is considered negligible the soil water balance method may only provide accurate crop ET measurements during periods with minimum (< 2 mm) or no P, since DP and RO during these periods is expected to be considerably low under these conditions (Testi *et al.* 2004). Partitioning of crop ET into transpiration (T) and soil evaporation (E_s) is also difficult using the soil water balance approach.

2.4.2 Micrometeorological approaches

2.4.2.1 Bowen ratio energy balance

The Bowen ratio energy balance method has been widely applied due to its relative simplicity and the precision with which vertical fluxes of water vapour vertical can be estimated (da Silva *et al.* 2006). In this method, crop ET is determined by estimating the latent heat flux (LE , $W\ m^{-2}$), through measurement of the following components of the energy balance: net radiation (R_n , $W\ m^{-2}$), soil heat flux (G , $W\ m^{-2}$) and sensible heat flux density (H , $W\ m^{-2}$), as expressed by the shortened energy balance equation (Rana and Katerji, 2000; Allen *et al.* 2011a):

$$LE = R_n - G - H \quad (2.2)$$

Values of R_n and G are measured directly using net-radiometers and G plates (Rana and Katerji, 2000; Allen *et al.* 2011a). Measurement of H is, however, complex as it requires accurate measurements of temperature gradients above the surface, and as a result, H is estimated as a residual of the energy balance, after an estimation of LE

using the Bowen ratio (β), R_n and G , as detailed in Equation 2.3 (Brotzge and Crawford, 2002):

$$LE = \frac{R_n - G}{1 + \beta} \quad (2.3)$$

The value of β is estimated using direct measurements of vertical gradients of temperature and relative humidity (Rana and Katerji, 2000):

$$\beta = \gamma \frac{\Delta T_a}{\Delta e_a} \quad (2.4)$$

where γ is the psychrometric constant in $\text{kPa } ^\circ\text{C}^{-1}$, ΔT_a is air temperature difference between two levels in $^\circ\text{C}$ and Δe_a is the air vapour pressure difference, measured at the same two levels in kPa . Other energy terms, such as heat stored or released in the plant, or the energy used in metabolic activities are often neglected, as these processes account for only a small fraction of the daily radiation balance, when compared with the other components (Allen *et al.* 1998). Under these simplifications, the turbulent diffusion coefficients of H are assumed to be equal to LE (da Silva *et al.* 2006).

Even though the Bowen ratio is considered an indirect method, its accuracy has been proven to be very good, particularly under semi-arid conditions (with mean absolute percent difference between measured and estimated values below 10%). Under arid conditions, crops are exposed to harsh environmental conditions and, as a result, ΔT can be quite high, while Δe_a is very low, making it possible to have accurate measurements of air vapour pressure for precise estimates of crop ET (Rana and Katerji, 2000).

The general advantages of the Bowen ratio method are the ability to measure crop ET even from vegetation surfaces which are not well-watered, the near elimination of the influence of turbulent transfer coefficients, the absence of surface and wind speed measurements, the requirement for relatively simple measurements of temperature and air vapour pressure at two heights, it forces the energy balance closure and that the measurements can be automated (Allen *et al.* 2011a). The disadvantages are that

it is relatively difficult to operate, it requires a medium to large fetch, the sensors are very fragile, it is heavily dependent on the accurate measurements of R_n and G for precise estimates of crop ET, it assumes similarity between the diffusion coefficient for heat and vapour which is only acceptable for neutral to moderately unstable conditions over smooth surfaces (Allen *et al.* 2011a). To ensure that accurate measurements of crop ET are obtained, particularly over rough surfaces like those found in orchard crops, a uniform fetch of sufficient distance should be used to establish an equilibrium boundary layer, sensors must be placed at a sufficient elevation above the canopy to avoid the roughness sub-layer, and representative measurements of R_n and G should be done (Allen *et al.* 2011a; Allen *et al.* 2011b).

2.4.2.2 Eddy covariance

The eddy covariance method for measuring crop ET consists of correlating the vertical fluctuations of wind from the mean (w') with the fluctuations from the mean in concentration of the transported admixture (q') at sufficient frequency (Foken *et al.* 2012). The covariance of these variables, in other words, their degree of variability as influenced by one another, is subsequently determined to obtain the contribution from all the significant sizes of eddies through their multiplication (Equation 2.5). The covariance of vertical wind speed (w' , m s^{-1}) and vapour density (q' , g m^{-3}) over a 30 min or an hourly time-scale gives a direct estimate of actual crop ET (Rana and Katerji, 2000).

$$LE = \lambda \overline{w'q'} \quad (2.5)$$

where λ is latent heat of vaporization (J g^{-1}).

Instantaneous values of w' can be measured using a sonic anemometer, while q' can be obtained using a fast response hygrometer or an infrared gas analyser. Both measurements are performed at a typical frequency of 5 – 20 Hz (Rana and Katerji, 2000).

The use of a fast response hygrometer to measure q' can be expensive and can create high frequency fallout caused by physical separation of the hygrometer from the sonic anemometer and, as a result, LE is normally computed as a residual of the energy balance to avoid this problem, thus making accurate measurements of R_n and G , as well as air temperature and w' which are used to compute H , extremely important in order to minimize the closure error (Allen *et al.* 2011a). Alternatively, LE can be obtained through direct measurements using an infrared gas analyser (IRGA), which in some designs is incorporated into the 3D sonic anemometer. In both methods to obtain LE, the lack of closure in the energy balance obtained using the eddy covariance technique is still a common problem (Allen *et al.* 2011a). As a rule, estimates of the scalar turbulent fluxes of H and LE are generally underestimated and the available energy ($R_n + G$) is usually overestimated (Wilson *et al.* 2002; Foken, 2008). The lack of closure of the energy balance has implications for how energy flux measurements should be interpreted and how these estimates should be compared with model simulations (Foken, 2008).

The energy balance closure is typically poor during nocturnal periods due to weak turbulent mixing, and better during daytime periods (afternoons better than mornings), possibly suggesting the underestimation of storage terms, which are usually larger in the mornings (Wilson *et al.* 2002). Several other possible causes of lack of closure in the energy balance have been suggested, such as horizontal advection, energy used by photosynthesis, change in storage of heat in the developing boundary layer below the instrumentation (causing flux divergence), frequency response of the sensor, separation and misalignment of sensors, error or bias in R_n or G measurement, insufficient fetch (the upwind distance from the tower with uniform features required to ensure that the measurement is representative of the underlying surface, usually set at a minimum of 1:100 m as a rule of Thumb or 100 m of upwind distance of vegetation for every meter above the ground up to the uppermost temperature and/or humidity sensor), non-stationarity of measured time series over the typical 30 min averaging periods so that covariance arising from very low frequency fluctuations is missed, interference from tower or instrument-mounting structures, influence of long-wave eddies (mainly found in heterogeneous fields) which cannot be measured with the eddy covariance method and increased number of corrections involved, which contribute to an increase in the turbulent flux (Mahrt, 1998; Twine *et al.* 2000; Stewart

and Howell, 2003; Allen *et al.* 2011a; Foken, 2008). Such corrections or transformations are the determination of time delay of all additional sensors, crosswind correction of the sonic temperature, correction for oxygen cross sensitivity of hygrometers, spectral corrections, conversion of the fluctuations of the sonic temperature into fluctuations of the actual temperature, density corrections of scalar fluxes of H₂O and CO₂, as well as iteration of the correction steps because of their interacting dependence and data quality analysis (Meyers and Baldocchi, 2005; Foken, 2008).

In general, the discrepancy in energy balance closure is a bias that varies from 0 to 30% (Twine *et al.* 2000). Wilson *et al.* (2002) found an average lack of closure of 20%, which prevailed in all the different vegetation types monitored and under climatic conditions ranging from Mediterranean to temperate and arctic. The magnitude of this discrepancy in the energy balance closure can be assessed using the following methods (Twine *et al.* 2000; Wilson *et al.* 2002; Harper, 2014): (1) determination of linear regression coefficients (slope and intercept) from the ordinary least squares (OLSs) relationship between the half-hourly estimates of the dependent flux variables (LE + H) against the independently derived available energy ($R_n - G$), with an intercept of zero and slope of one representing ideal closure; (2) the reduced major axis (RMA) method, which switches the independent and dependent variables and evaluates the slope as the geometric mean of the OLSs; (3) the method of moments (MMs), which evaluates the effect of different hypothetical error estimates (10 to 50%) on the linear regression slope; (4) the calculation of the energy balance ratio (EBR), which is the ratio between cumulative sums of LE + H and $R_n - G$, with EBR = 1 representing full closure.

The problem of lack of closure in eddy covariance flux measurements can be reasonably solved using one of the following methods: (1) calculation of LE flux as a residual of the surface energy balance and (2) assuming that the Bowen ratio (β) is measured accurately by the eddy covariance system and adjusting both LE and H to preserve β and conserve energy (Twine *et al.* 2000). The first method is dubious because measurements of LE are completely ignored and assumes all other measurements are accurate, while the second is more reliable and it has been successfully used to resolve the lack of closure in crop ET measurements with the

eddy covariance technique in irrigated orange orchards under semi-arid Mediterranean conditions (Consoli and Papa, 2013).

The eddy covariance system has similar advantages to the Bowen ratio energy balance method. Both methods can also be used indirectly to determine soil evaporation (E_s) from a cropped field, as the difference between measured crop ET and transpiration (T) measured with a sap flow method (Zeggaf *et al.* 2008; Holland *et al.* 2013). However, like most methods, it also has disadvantages which include a high number of corrections needed in order to obtain accurate estimates of crop ET, the energy balance closure error is often in the range of 10 – 30%, it requires substantial fetch (generally between 50 – 100 times the height of the instruments above the zero plane displacement height), changes in wind and flow line direction may increase measurement errors, the instrumentation is relatively fragile and expensive and it requires well-trained personnel for its installation, maintenance and operation (Allen *et al.* 2011a). Accurate measurements of crop ET can, however, be done using the eddy covariance system, provided that the basic requirements are fulfilled, which include the following (Allen *et al.* 2011a; Allen *et al.* 2011b): establishment of an adequate fetch; sufficient elevation of the instrumentation above the canopy to reduce roughness sub-layer distortions and to increase eddy size to match the sensor path length; corrections of the eddy covariance flux measurements and use of qualified personnel, with knowledge of physics of turbulence.

2.4.2.3 Surface renewal method

The operational principle of the surface renewal method to measure crop ET is based on the evidence that air near a surface is renewed by ascendant ambient air as well as on the analysis of energy balance of air parcels that reside ephemerally within the crop canopy during the turbulent exchange process (McElrone *et al.* 2013). In this method, H ($W m^{-2}$) is estimated based on measurements of high-frequency air temperature fluctuations, and LE ($W m^{-2}$) is subsequently obtained as a residual of the energy balance equation (Drexler *et al.* 2004).

$$H = \alpha \rho_a c_p \left(\frac{a}{d+s} \right) z \quad (2.6)$$

where α is a correction factor for unequal heating below the sensors and it depends on z , which is the measurement height (m), on canopy structure and on thermocouple size; α is usually assumed equal to 0.5 for orchard crops (Mengistu and Savage, 2010) or it can be determined for a specific crop using structure functions of air temperature as described by Snyder *et al.* (1996); ρ_a is air density (g m^{-3}), C_p is the specific heat of air at constant pressure ($\text{J g}^{-1} \text{K}^{-1}$) and the ratio $\left(\frac{a}{d+s}\right)$ represents the mean change in temperature ($^{\circ}\text{C}$ or K) with time (s) during the sampling interval (usually 30 min), where a is the mean ramp amplitude, d is the ramp period and s is the quiescent period between ramps.

The surface renewal is a relatively new, simple and low-cost method for estimating scalar fluxes, and as a result, the method can easily be replicated for different seasons of measurements under field conditions (Mengistu and Savage, 2010). In addition, more accurate estimates of H are obtained with the surface renewal when the instrumentation is installed close to the canopy, which makes the method applicable to fetch limited vegetation, in contrast to the eddy covariance method (Castellví and Snyder, 2009). The surface renewal method also uses a lower measurement frequency (4 Hz), compared to the eddy covariance method (10 Hz), thus involving a smaller amount of data, which allows easier and cheaper computation of H fluxes (Barbagallo *et al.* 2009). Sensible heat can also be measured accurately under all conditions of atmospheric stability without the need for calibration of the system, when the data is measured at about 90% of the canopy height (Spano *et al.* 2000). However, the technology is very dependent on the use of a good sonic anemometer (a two-dimensional sonic anemometer should be used rather than cup anemometers) for increased accuracy of H measurements (Castellví and Snyder, 2009). In addition, measurements of R_n and G should be accurate in order to obtain good estimates of LE (Drexler *et al.* 2004). Good estimates of crop ET were obtained for grapevines, citrus and peaches, taking into account such considerations when using the surface renewal method (Spano *et al.* 2000; Barbagallo *et al.* 2009; Castellví and Snyder, 2009).

2.4.3 Remote sensing approach

2.4.3.1 Remote sensing energy balance method

Remote sensing represents a more recent technology for estimating soil evaporation and crop ET from large, heterogeneous surface areas, contrarily to conventional ground-based ET measurement techniques such as eddy covariance and Bowen ratio, which are limited to relatively small, homogeneous footprints that rarely exceed 1 – 2 km (Hassan-Esfahani *et al.* 2015). The main advantage of this technique lays in the fact that it can provide more affordable measurements of ET over large, heterogeneous fields of about 20 000 km² (Allen *et al.* 2011a). Whereas, for relatively small fields, like most fruit tree orchards, implementing this method can be very expensive. Besides, satellite images are only obtained periodically for a specific location, which makes real-time measurements of crop ET impossible, thus limiting its applicability for accurate irrigation scheduling (Allen *et al.* 2011a). Aerial imagery has, however, demonstrated to be useful for irrigation water management, through an accurate assessment of surface soil water content status of large irrigated fields using high-resolution multi-spectral imagery and artificial neural networks (Hassan-Esfahani *et al.* 2015).

2.4.4 Plant physiology approaches

Measurements of T are important for quantifying stomatal function and carbon dioxide uptake which are directly linked to the process of photosynthesis and crop productivity, for calibration and validation of soil-plant-atmosphere continuum models, as well as a diagnostic tool where flow through the xylem is thought to be impeded by pathological organisms (Dragoni *et al.* 2005; Vandegehuchte and Steppe, 2013). Such measurements can be obtained using either chamber systems or sap flow methods (Rana and Katerji, 2000).

2.4.4.1 Chamber systems

Chamber systems for gas exchange measurements in orchard crops are more accurately made at the whole-plant level using large canopy chambers, but due to

their high operational costs and complexity, their application is very limited (Moriana *et al.* 2002; Dragoni *et al.* 2005; Pérez-Priego *et al.* 2010). Sap flow methods are the most commonly used to measure T of orchard crops, and as a result, this review will only discuss these methods.

2.4.4.2 Sap flow methods

There are several important methods for measurements of sap flow in plants, which can be grouped in two distinct categories (Vandegehuchte and Steppe, 2013): (1) heat balance methods, which integrate flow in the entire stem or in a large sections of the plant (stem heat balance and trunk heat balance methods) and (2) sap flux density methods, which determine the amount of sap flowing through a certain surface area per time (classified as empirical, continuous methods: thermal dissipation and heat deformation or theoretical heat pulse methods which include compensation heat pulse and heat ratio methods). Sap flux density methods allow not only the determination of whole-plant water use, but also an in-depth knowledge of flow directions and special flow distributions, of which heat pulse methods seem to outperform the continuous methods as they often do not require specific calibrations and they are less susceptible to natural temperature gradients (Vandegehuchte and Steppe, 2013).

The heat-pulse methods are widely used for sap flow measurements of woody plants due to its numerous advantages. These methods provide measurements of sap flow in tree stems with minimal disruption to the sap stream, the measurements are reliable and affordable, they require simple instrumentation and have low power requirements; they provide good time resolution of sap flow, they are well suited to automatic data collection and storage, and they allow simultaneous measurements on numerous trees (Green *et al.* 2003). With the heat-pulse methods, mass flow of sap is determined from the velocity of a short pulse of heat moving through xylem tissue by conduction and convection (Bleby *et al.* 2004). The determination of mass flow of sap is based on a set of analytical solutions to the following heat flow equation (Marshall, 1958):

$$\rho_w c_f \frac{dT_a}{dt} = \frac{d}{dx} \lambda_x \frac{dT_a}{dx} + \frac{d}{dy} \lambda_y \frac{dT_a}{dy} - a u \rho_s c_s \frac{dT_a}{dx} + Q \quad (2.7)$$

Where ρ_w and ρ_s are the densities (kg m^{-3}) of fresh wood and sap, respectively; c_f and c_s are the specific heat capacities ($\text{J s}^{-1} \text{m}^{-1} \text{K}^{-1}$) of fresh wood and sap, respectively; dT_a is the temperature departure from ambient (K); t is the time (s); λ is the thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$) in the axial (x) and tangential (y) directions; a is the fraction of xylem cross-sectional area occupied by sap streams moving with a velocity u in the x direction; and Q is the amount of internal heat that is released from the heater (W m^{-3}). There are two techniques within the heat-pulse category, which are currently most commonly used by researchers: the compensation heat-pulse method (CHPM) which was developed first, and the heat-ratio method (HRM) which was developed later to address the limitations of the CHPM, which fails to measure reverse, low and very high flux densities (Bleby *et al.* 2004; Vandegehuchte and Steppe, 2013).

The HRM measures the ratio of the increase in temperature, following the release of a pulse of heat, at points equidistant downstream and upstream from a line heater. The heat pulse velocity (V_h , m s^{-1}) is subsequently calculated as follows (Burgess *et al.* 2001):

$$V_h = \frac{D_{ax}}{x} \ln \left(\frac{\Delta T_{down}}{\Delta T_{up}} \right) \quad (2.8)$$

where D_{ax} ($\text{m}^2 \text{s}^{-1}$) is axial thermal diffusivity of the sapwood, x (m) is the distance between heat source (heater) and temperature sensors, and ΔT_{down} and ΔT_{up} are the increases in temperature (relative to ambient) at equidistant points from the heater. Figure 2.4 is a schematic diagram of the heat-pulse probe configuration in a tree stem, which can be applied for both CHPM and HRM, depending on the distances at which temperature probes are installed away from the heater.

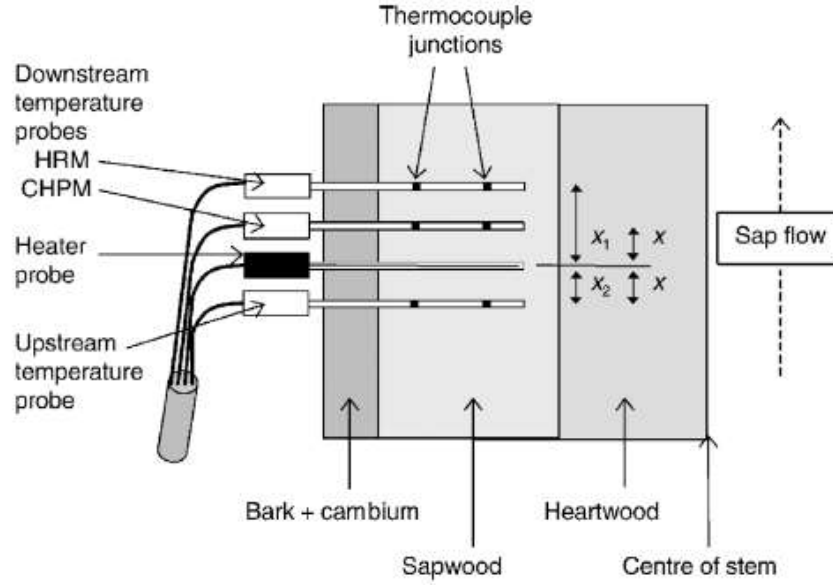


Figure 2.4 Schematic diagram showing the configurations of heat-pulse probes implanted radially in a stem (Bleby *et al.* 2004). For the CHPM, the downstream temperature is installed at a distance x_1 above the heater and the upstream probe at a distance x_2 below the heater. For the HRM, temperature probes are installed at the same distance x above and below the heater, which is typically 5 mm. Temperature sensors (Type-T thermocouples) are located at various depths in the conducting sapwood below the sapwood-cambium boundary).

Axial thermal diffusivity (D_{ax}) is a crucial parameter to determine sap flux density when using the HRM, as it measures how quickly the sapwood can absorb or release heat from or to its surroundings (Bouguerra, 2001; Vandegehuchte and steppe, 2012). According to Bouguerra (2001), the parameter D_{ax} can be determined as follows:

$$D_{ax} = \frac{K_{ax}}{\rho_c} \quad (2.9)$$

where K_{ax} is the axial thermal heat conductivity and ρ_c is the volumetric heat capacity, determined as follows (Skaar, 1988; Vandegehuchte and steppe, 2012):

$$K_{ax} = K_w(MC - MC_{FSP}) \frac{\rho_d}{\rho} + 0.04186 \left[21.0 - 20.0 \left(1 - c_g \left(\frac{\rho_w}{\rho_{cw}} + MC_{FSP} \right) \right) \right] \quad (2.10)$$

$$\rho_c = \frac{W_d C_d + C_w (w_f - w_d)}{V} \quad (2.11)$$

where K_w is the thermal conductivity of water ($0.5984 \text{ W m}^{-1} \text{ K}^{-1}$), c_g the specific gravity of wood (dry mass per fresh volume divided by the density of water), MC the water content of the sapwood, MC_{FSP} the water content at the fibre saturation point (generally taken as 30%), ρ_{cw} the cell wall density (1530 kg m^{-3}) and ρ_d and ρ the density of dry wood and water respectively; w_f is the fresh and w_d the oven-dried weight of the wood sample (kg), V is the volume of the wood sample (m^3) and c_w and c_d the specific heat capacity of water and dry wood. Parameters MC, ρ_d and those used to calculate ρ_c are determined from a wood core sample (Vandegehuchte and Steppe, 2013).

Given a good estimation of D_{ax} , the HRM has proven its value for measuring low and reverse flows (Vandegehuchte and Steppe, 2013). It is, however, limited for high sap flux densities ($>45 \text{ cm}^3 \text{ cm}^{-2} \text{ h}^{-1}$) (Burgess *et al.* 2000). Besides, the HRM needs to be calibrated for species with sapwood that is not thermally homogeneous in which the distribution of sap-conducting elements is markedly non-uniform, or if the interstitial distances between elements are too large for the time required for thermal equilibration between sap and woody matrix to be considered negligible (Smith and Allen, 1996). The HRM is also invasive, requiring the insertion of probes into the xylem, which disrupts the sap stream and alters the thermal homogeneity of the surrounding sapwood, causing a systematic underestimation of sap flow rates (Fernández *et al.* 2006; Steppe *et al.* 2010). In order to overcome such limitation, Burgess *et al.* (2001) developed a numerical model to supply appropriate wound correction coefficients for the adjustment of V_h measured with the HRM. Corrected heat pulse velocities (V_c , m s^{-1}) are subsequently used to determine sap velocities (V_s , m s^{-1}) by measuring the fractions of sap and wood in xylem and accounting for their differing densities and specific heat capacities (Barret *et al.* 1995):

$$V_s = \frac{V_c \rho_d (c_d + MC c_w)}{\rho c_w} \quad (2.12)$$

The product of V_s and cross-sectional area of conducting sapwood results in volumetric sap flow. Many authors have, however, still noted systematic

underestimations of sap flow rates, even after taking into consideration wounding correction coefficients (Fernández *et al.* 2006; Taylor *et al.* 2015). This problem is often solved through further calibration using whole-tree T measured with large lysimeters (Fernández *et al.* 2006) or T data estimated as the residual of simultaneous measurements of crop ET and E_s (Taylor *et al.* 2015).

2.4.5 Measured water use for various tree nut crops

Whilst there are a number of publications on measured pecan ET (Miyamoto, 1983; Miyamoto, 1990; Sammis *et al.* 2004; Samani *et al.* 2009; Samani *et al.* 2011), there is almost a complete lack of information for other tree nut crops, particularly for macadamias. Table 2.3 summaries the published water use values for the different tree nut crops, including the measurement method, climatic conditions and irrigation system under which measurements were conducted.

Table 2.3 Measured water use published for tree nut crops under various conditions of climate and irrigation systems.

Tree nut crop	Tree age (years)	f _c Max (%)	ET/ T				Measurement method	Irrigation method	Climate	Reference
			Annum _{Total} (mm)	Season _{Total} (mm)	Day _{Max} (mm)	Day _{Max} (L)				
Pecan	5		ET = 530				Soil water balance	Flood	Arid, desert	Miyamoto, 1990
	10		ET = 760				Soil water balance	Flood	Arid, desert	Miyamoto, 1990
	15		ET = 920				Soil water balance	Flood	Arid, desert	Miyamoto, 1990
	20		ET = 1040				Soil water balance	Flood	Arid, desert	Miyamoto, 1990
	25		ET = 1160				Soil water balance	Flood	Arid, desert	Miyamoto, 1990
	30	65 - 70	ET = 1420	ET = 1215	ET = 9	ET = 800	Eddy covariance	Flood	Arid, desert	Sammis <i>et al.</i> 2004
	40		ET = 1413		ET = 9	ET = 729	Eddy covariance	Flood	Arid, desert	Samani <i>et al.</i> 2009
Pistachio	10	> 60		ET = 1018	ET = 8	ET = 231	Soil water balance	Micro-sprinkler	Arid, desert	Goldhamer <i>et al.</i> 1986
	11	57		ET = 1024	ET = 9	ET = 271	Soil water balance Compensation Heat	Micro-sprinkler	Semi-arid	Iniesta <i>et al.</i> 2008
	12				T = 8		Pulse	Sprinkler	Mediterranean	Villalobos <i>et al.</i> 2013
Walnut	7				T = 8	Compensation Heat Pulse	Drip	Mediterranean	Villalobos <i>et al.</i> 2013	
Almond	12			ET = 1450	ET = 12	ET = 420	Eddy covariance	Sprinkler	Semi-arid, Mediterranean	Stevens <i>et al.</i> 2012
Cashew	5					T = 28	Thermal dissipation	Drip	Tropical	Blaikie <i>et al.</i> 2001
Macadamia	8					ET = 80	Lysimetry		Subtropical	Stephenson <i>et al.</i> 2003

The ET of fruit trees is a complex and dynamic process, as it is influenced by several factors including local environmental conditions, plant morphology and physiological characteristics, as well as field management practices (Jones *et al.* 1985; Naor, 2006). Values of ET and/ or T published for the different tree nut crops included in Table 2.3 indicate that evergreen tree species are likely to use a lot less water (28 to 80 L day⁻¹) than deciduous species (231 to 800 L day⁻¹) on a daily basis. This is not surprising, as evergreen species tend to exhibit strong stomatal control over T to avoid possible environmental stress (Andersen, 1994; Stephenson and Trochoulias, 1994). Besides, leaves of evergreen species possess a higher degree of sclerophylly and succulence, allowing these species to be better adapted to drought periods than deciduous species (Burghardt and Riederer, 2003). Such adaptations permit evergreen species to use soil water more gradually, preventing the occurrence of xylem embolism and cavitation during extreme drought conditions (Sperry, 2000; Poggi *et al.* 2007; Ennajeh *et al.* 2008). Crop water use comparisons between deciduous and evergreen tree nut species should, however, be made with caution as detailed information on various factors affecting crop water use is generally not available under similar conditions of tree size, climate and crop management to enable a fair comparison. As evident from Table 2.3, there is generally little information published on ET or T of tree nut crops, and as a result, a detailed assessment on how the water use of these crops is influenced by various factors is almost impossible. Even though the water use of pecans has been reported more widely than the other tree nut crops, all the studies have been conducted under similar conditions of climate and irrigation system, which makes it difficult to use these experimental results for irrigation water management purposes in pecan orchards established in areas with different climatic conditions or using different irrigation systems. Thus, it is crucial to assess whether there are currently any crop models for the estimation of water use of tree nut crops, as these models will help extrapolate measurement results to conditions where experiments have not been conducted.

2.5 CROP WATER USE MODELLING

Various modelling approaches are used to predict T, crop ET and/ or its partitioning into E_s and T, under non-limited soil water conditions, starting from simple, empirical approaches to the more complex, mechanistic approaches (Rana and Katerji, 2000;

Egea *et al.* 2011; Dong *et al.* 2014; Kool *et al.* 2014; Verhoef and Egea, 2014; Subedi and Chávez, 2015). Simple, empirical approaches are more easily parameterized, but they are often site-specific, whilst mechanistic approaches can be more widely transferred, provided that the required, often difficult to determine, input parameters are accurately obtained (Leenhardt *et al.* 1995). Depending on the central principle for estimating crop water use, these modelling approaches can be categorized into three main groups: (1) soil water balance approaches, which predict crop water use as the residual difference between soil water inputs (rainfall and irrigation) and outputs (runoff, drainage and changes in soil water storage within the root zone) (Leenhardt *et al.* 1995); (2) crop coefficient approaches, which make use of a crop coefficient that integrates the effect of characteristics distinguishing a typical crop from the grass reference (Allen *et al.* 1998); and (3) stomatal conductance approaches, which model the response of stomata to changes in the local environmental conditions of the crop (Damour *et al.* 2010). A description of each category of modelling approaches is presented below.

2.5.1 Soil water balance approach

Soil water balance models for the estimation of crop ET, T and E_s can be grouped in two main categories: (1) simple models (which use the cascading or tipping bucket principle to estimate root water uptake) and (2) complex models (which model root water uptake using soil water infiltration and redistribution functions) (Rana and Katerji, 2000; Dong *et al.* 2014). In simple models, the soil is treated as a collection of water reservoirs, filled by rainfall and/or irrigation and emptied by crop ET and drainage (Leenhardt *et al.* 1995; Rana and Katerji, 2000). Examples of such models include those where the soil profile is treated as a bucket into which water flows until it is full, or more advanced ones where the soil profile is divided into different layers, with water cascading from upper to lower layers when the upper layers reach field capacity (de Jong and Bootsma, 1996). An example of such models include the one-dimensional Soil Water Balance (SWB) model (Annandale *et al.* 1999). In complex models, the water flow in the soil is described by mathematical functions of soil water movement, such as the two-dimensional Richard's equation. The HYDRUS-2D and SWB-2D soil water balance models are clear examples of models within this category (Skaggs *et al.* 2004; Annandale *et al.* 2004).

The simple and complex approaches of soil water balance modelling both present advantages and disadvantages. The applicability of complex models is constrained by the accuracy of pseudo-transfer functions used for the estimation of water transfer and by the procedures used for estimating the boundary conditions of the soil-plant-atmosphere system. However, in simple models, although they are simpler, there are difficulties in determining the soil water storage as a function of the soil and root depth (Rana and Katerji, 2000). The availability of data often determines which modelling approach can be used. More advanced soil water balance modelling approaches generally require daily or hourly observations of rainfall and estimated potential ET. Simpler models require less soil input parameters (field capacity and permanent wilting point values, either single values applicable to the entire soil profile, or a set of values of each layer) than more complex models (which require water retention characteristics and hydraulic conductivity functions for each soil layer). Simple modelling approaches often give accurate estimates of water use for annual crops (de Jong and Bootsma, 1996; Dong *et al.* 2014). Complex models, on the other hand, may be more suitable for estimating crop water use of perennial tree crops, as these often simulate multiple-dimensional water movement in the soil, which better accounts for root water uptake for T and variability of E_s due to non-uniform wetted areas (Annandale *et al.* 2004). In these models, ET, T and E_s are computed using a mechanistic supply or demand-limited approach (Skaggs *et al.* 2004; Annandale *et al.* 2004).

Even though complex models may be difficult to operate, the estimated ET may be more accurate, provided that the required hydraulic parameters (such as soil water content at saturation, residual soil water content and saturated hydraulic conductivity) are well determined (Leenhardt *et al.* 1995; Skaggs *et al.* 2004). Failing to meet the input parameter requirements, the soil water balance approach may not be accurate enough to estimate crop ET. This is particularly true for fruit tree species where complex soil-plant-atmosphere continuum interactions occur, which are often aggravated by the fact that such plant species exhibit high levels of stomatal control that can override the effect of root water uptake, in which the functional principle of soil water balance models is based (Dong *et al.* 2014). This may help explain why the applicability of soil water balance models is very limited for fruit tree species.

2.5.2 Crop coefficient approach

The simplest and most widely used form of the crop coefficient approach consists of estimating crop ET by multiplying the reference crop ET (ET_0), by a single crop coefficient (K_c). Estimates of crop ET using this approach represent ET rates under well-watered, optimal management conditions (Allen *et al.* 1998):

$$ET = K_c ET_0 \quad (2.13)$$

Reference crop evapotranspiration was initially conceptualized as the evapotranspiration rate from a hypothetical short grass reference surface, growing under optimum management conditions (Allen *et al.* 1998). Later on, Pereira *et al.* (1999) suggested that, for more accurate predictions of crop ET, ET_0 should be distinctly defined for three groups of crop categories based primarily on crop height, namely 0.12 m (short grass), 0.5 to 0.7 m (alfalfa) and 2.0 to 3.0 m (tall maize). This was suggested considering the fact that the aerodynamic resistance parameter initially included in the ET_0 equation developed by Allen *et al.* (1998) is highly variable depending on crop height and density (Pereira *et al.* 1999). As a result, a more standardized form of the Penman-Monteith equation was developed, which applies for both, short and tall vegetation (Allen *et al.* 2006; Pereira *et al.* 2015):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \left(\frac{C_n}{T_a} + 273 \right) u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (2.14)$$

where ET_0 is the standardized reference ET, in mm d^{-1} for daily time steps, or mm h^{-1} for hourly or shorter time steps; R_n is the calculated net radiation at the crop surface, $\text{MJ m}^{-2} \text{d}^{-1}$ for daily time steps, or $\text{MJ m}^{-2} \text{h}^{-1}$ for hourly or shorter time steps; G is the soil heat flux density at the soil surface, $\text{MJ m}^{-2} \text{d}^{-1}$ for daily time steps, or $\text{MJ m}^{-2} \text{h}^{-1}$ for hourly or shorter time steps; T_a is the mean daily or hourly air temperature at 1.5 to 2.5 m height, $^{\circ}\text{C}$; u_2 is the mean daily or hourly wind speed at 2 m height, m s^{-1} ; e_s is the saturation vapour pressure at 1.5 to 2.5 m height, kPa, calculated for daily time steps as the average of saturation vapour pressure at maximum and minimum air temperature and for hourly time steps using hourly average air temperature; e_a is the mean actual vapour pressure at 1.5 to 2.5 m height, kPa; Δ is the slope of the

saturation vapour pressure-temperature curve, $\text{kPa } ^\circ\text{C}^{-1}$; γ is the psychrometric constant, $\text{kPa } ^\circ\text{C}^{-1}$; C_n is the numerator constant that changes with reference type and calculation time step, $\text{K mm s}^3 \text{Mg}^{-1} \text{d}^{-1}$ or $\text{K mm s}^3 \text{Mg}^{-1} \text{h}^{-1}$; C_d is the denominator constant that changes with reference type and calculation time step, s m^{-1} . Values for parameters C_n and C_d are given in Table 2.4 (Pereira *et al.* 2015).

Table 2.4 Values for C_n and C_d coefficients for calculation of reference ET (Pereira *et al.* 2015).

Calculation time step	Short reference, ET_o (Clipped grass)		Tall reference, ET_r (Alfalfa)		Units for ET_o, ET_r	Units for R_n, G
	C_n	C_d	C_n	C_d		
Daily	900	0.34	1600	0.38	mm day^{-1}	$\text{MJ m}^{-2} \text{day}^{-1}$
Hourly during daytime	37	0.24	66	0.25	mm hr^{-1}	$\text{MJ m}^{-2} \text{hr}^{-1}$
Hourly during night-time	37	0.96	66	1.7	mm hr^{-1}	$\text{MJ m}^{-2} \text{hr}^{-1}$

The effects of crop characteristics on the estimation of ET, using Equation 2.13, are accounted for by including a single K_c , which takes into consideration the effects of crop type, variety and development stage, as well as, differences in resistance to T , crop height, crop roughness, reflection, ground cover and crop rooting characteristics (Allen *et al.* 1998). Values of K_c will also fluctuate as affected by climatic conditions and crop management practices (Wang *et al.* 2007). Table 2.5 illustrates some of these variations in K_c for a number of deciduous and evergreen fruit tree crops, growing under well-managed conditions in sub-humid climates (Allen *et al.* 1998). Values of $K_{c \text{ initial}}$, $K_{c \text{ mid}}$ and $K_{c \text{ end}}$ represent K_c values during the initial stage of the growing season (from the time of pruning until 10% canopy cover), mid-season stage (from effective full canopy cover until the start of leaf senescence) and late stage (starting from the beginning of leaf senescence until the harvest date).

From Table 2.5, it is evident that evergreen fruit tree species (using citrus and olives as examples) have lower maximum K_c values during the midseason period (0.6 – 0.85), as compared to deciduous species (0.9 – 1.2). The differences in the magnitude of K_c values are likely related to physiological and morphological differences between

these two distinct groups of fruit tree species. Evergreen species generally have smaller fluctuations of leaf water potentials and leaf water content per unit of dry mass throughout the season, than leaves from deciduous species (Sobrado, 1986; Sobrado, 1991). As a result, evergreen species require smaller gradients of water potential between leaves and soil, resulting in lower soil water uptake and T rates comparatively to deciduous species (Eamus, 1999), which is a physiological adaptation mechanism of the former species to avoid plant water stress.

Table 2.5 Single crop coefficients (K_c) during different growth stages, for well-managed fruit tree crops in sub-humid climates (Allen *et al.* 1998).

Fruit tree crop	Maximum h (m)	K_c		
		Initial	Mid-season	End
Almonds, no ground cover	5	0.4	0.9	0.65
Apples, Cherries, Pears				
no ground cover, killing frost	4	0.45	0.95	0.70
no ground cover, no frost	4	0.60	0.95	0.75
active ground cover, killing frost	4	0.50	1.20	0.95
active ground cover, no frost	4	0.80	1.20	0.85
Stone fruit (peaches, apricots, pears, pecans)				
no ground cover, killing frost	3	0.45	0.90	0.65
no ground cover, no frost	3	0.55	0.90	0.65
active ground cover, killing frost	3	0.50	1.15	0.90
active ground cover, no frost	3	0.80	1.15	0.80
Citrus, no ground cover				
70% canopy	4	0.70	0.65	0.70
50% canopy	3	0.65	0.60	0.65
20% canopy	2	0.50	0.45	0.55
Citrus, with active ground cover or weeds				
70% canopy	4	0.75	0.70	0.75
50% canopy	3	0.80	0.80	0.80
20% canopy	2	0.85	0.85	0.85
Olives (40 to 60% canopy cover)	3 - 5	0.65	0.70	0.70
Pistachios, no ground cover	3 - 5	0.40	1.10	0.45
Walnuts	4 - 5	0.50	1.10	0.65

Such physiological adaptation of evergreen species is mainly attributed to their leaves which are sclerophyllous or xeromorphic, with sclerified bundle sheath tissue, wax

coating, pubescence or a leathery texture, thus creating a barrier against water loss (Sobrado, 1986). Evergreen species, such as citrus, may also have high internal resistances to water movement, which may limit their ability of water supply as demanded by the atmosphere (Sinclair and Allen, 1982). Marsal *et al.* (2014) further suggested that fruit tree species with higher vegetative vigour (faster, continuous growing shoots, as seen in deciduous species) generally have higher maximum hydraulic conductances, which may lead to higher maximum rates of T and therefore higher basal crop coefficients (defined as the ratio of T over ET_o , symbolized by K_{cb}) as compared to evergreen species.

As values of K_c fluctuate throughout the growing season, as influenced by changes in climate, tree size and canopy development, various models have been developed to adjust K_c according to these changes, in order to obtain more accurate predictions of crop ET (Miyamoto, 1983; Allen *et al.* 1998; Johnson *et al.* 2000; Sammis *et al.* 2004; Wang *et al.* 2007; Allen and Pereira, 2009; Samani *et al.* 2011). Changes in climate may result in variations in the length of the different growth stages, thus affecting the shape of the K_c curve (Sammis *et al.* 2004) or in the magnitude of K_c values, as a result of variations in wind speed (u_2) and minimum daily relative humidity (RH_{min}) from one climatic region to another (Allen and Pereira, 2009). Increased u_2 and decreased RH_{min} cause the ratio of ET over grass ET_o to increase due primarily to differences in roughness between taller agricultural crops and the clipped grass reference (Allen and Pereira, 2009). This is the reason why Allen *et al.* (1998) suggested that K_c values published in FAO-56, which were developed under sub-humid climatic conditions at $u_2 = 2 \text{ m s}^{-1}$ and $RH_{min} = 45\%$, should be adjusted to specific conditions of u_2 and RH_{min} for more accurate estimates of crop ET using grass ET_o . The procedure developed by Allen *et al.* (1998) for the adjustment of K_c due to differences in roughness is, however, limited to use with K_c values published in FAO-56 only. While changes in K_c due to intra and inter seasonal climatic variations are well accounted for using ET_o when estimating crop ET with the FAO-56 model, the procedure does not consider the influence of climate on the rate of canopy development, which is quite significant for some deciduous fruit tree species like pecans for example (Miyamoto, 1983; Sammis *et al.* 2004; Wang *et al.* 2007; Samani *et al.* 2011). In an attempt to overcome this limitation, researchers have developed simple models using thermal time to adjust the shape of the K_c curve in order to account for changes in the rate of canopy

development (Miyamoto, 1983; Sammis *et al.* 2004; Marsal *et al.* 2014). Simple thermal time or growing degree day (GDD) equations accumulate thermal time linearly with increasing temperature above a constant crop-specific base temperature, which makes them easily applicable to conditions where they were developed (Samani *et al.* 2011), but perhaps less applicable outside the area of calibration. Such models have been developed to adjust K_c of pecans to specific climatic conditions (Miyamoto, 1983; Sammis *et al.* 2004), while for macadamias there is very little known about the process of their water use (Carr, 2012a). Adjustments of K_c values to changes in tree size and canopy development are often made using simple relationships between K_c values and measurements of fractional canopy cover (f_c), in other words, the proportion of the orchard floor that is covered by the tree canopy (Johnson *et al.* 2000; Snyder *et al.* 2000; Johnson and Ayars, 2002; Ayars *et al.* 2003; Williams and Ayars, 2005; Andales *et al.* 2006; Goodwin *et al.* 2006; Samani *et al.* 2011). Short-time measurements of canopy cover are either done using expensive equipment, such as ceptometers or plant canopy analysers (Johnson *et al.* 2000; Ayars *et al.* 2003), or simple but time-consuming methods like shaded area measurements using the grid method (Johnson and Ayars, 2002; Ayars *et al.* 2003). This may be a limitation for monitoring canopy growth and development of fruit trees more frequently, which is a requirement for increased accuracy of crop ET predictions. As a result, models have been used to predict real-time fluctuations of solar radiation interception based on canopy characteristics and orchard configurations (Annandale *et al.* 2004; Oyarzun *et al.* 2007; Abraha and Savage, 2010).

Various generic models have been used to predict solar radiation interception by fruit tree canopies, including the models developed by Annandale *et al.* (2004), Oyarzun *et al.* (2007) and Abraha and Savage (2010). In these models, the following basic inputs are needed: tree height, canopy width and depth, bare stem height, latitude, longitude, altitude, date, standard meridian, tree spacing, row orientation and daily solar radiation (Annandale *et al.* 2004; Oyarzun *et al.* 2007; Marsal *et al.* 2013). In addition to these inputs, the models by Annandale *et al.* (2004) and Abraha and Savage (2010) also require leaf area density, while the model by Oyarzun *et al.* (2007) requires canopy porosity data. These parameters are relatively difficult to obtain, especially leaf area density, as the calculation involves leaf area index measurements and estimations of canopy volume. Leaf are index of tree canopies is measured using

high-cost leaf area meters or canopy analysers, which can be difficult to operate. Canopy volume estimates using a manual method are subjected to errors due to the assumptions involved with canopy shape and the actual measurements of canopy size which are required to determine canopy volume (Lee and Ehsani, 2009). Due to these uncertainties, accurate estimates of solar radiation interception using the model by Annandale *et al.* (2004) and Abraha and Savage (2010) are usually obtained through model calibration for each fruit tree species using tube solarimeters, which are expensive, and fragile and therefore require regular maintenance. The model by Oyarzun *et al.* (2007), on the other hand, is more easily applied than the model by Annandale *et al.* (2004) and Abraha and Savage (2010), due to the fact that it uses canopy porosity instead of leaf area density, which is a relatively easier parameter to obtain (Johnson and Ayars, 2002; Ayars *et al.* 2003). In addition, the model of Oyarzun *et al.* (2007) has wider applicability than those developed for a single planting pattern like the model of Annandale *et al.* (2004), as it can be used for different types of orchard configurations including hedgerow, overhead trained or isolated trees planted in rectangular patterns. Moreover, this model not only estimates intercepted solar irradiance but also intercepted photosynthetic active radiation (PAR), which neither the model of Annandale *et al.* (2004) nor the model of Abraha and Savage (2010) do. Estimates of PAR are very important to accurately model T since it is the energy requiring process, with a direct influence on photosynthesis and crop productivity (Villalobos *et al.* 2013). The model by Oyarzun *et al.* (2007) has been parameterized for grapevines, cherries, pears and apples, but not for pecans and macadamias.

The single K_c approach is not the most appropriate procedure to estimate crop ET for conditions of variability of wetting of the soil surface, particularly when ground cover is minimal. Changes in soil surface wetness are influenced by the frequency and duration of rainfall and irrigation events, as well as by the type of irrigation system or strategy practiced, and these cannot be entirely accounted for using canopy cover estimates. This is particularly noticeable under conditions of partial canopy cover, when soil evaporation (E_s) is expected to be considerable component of ET due to increased energy reaching the soil surface. Due to this limitation, a dual K_c approach was developed to estimate crop ET, which splits the K_c into a T (K_{cb}) and E_s (K_e) component (Allen *et al.* 1998):

$$ET = (K_{cb} + K_e)ET_o \quad (2.15)$$

$$T = K_{cb}ET_o \quad (2.16)$$

$$E_s = K_eET_o \quad (2.17)$$

Values for K_{cb} and K_e components of the dual K_c approach can be determined for both stressed and non-stressed soil water conditions. The determination of the K_e component accounts for variations in irrigation strategies, including wetted surface area and wetting frequency by irrigation and rainfall events, which are required for accurate predictions of E_s (Allen *et al.* 2005). The determination of the K_{cb} component, on the other hand, allows for estimation of T , which is useful for assessing how much water is effectively used by the crop, which will directly determine crop productivity. Thus, this ET partitioning approach has the potential to make significant contributions for improved decisions in irrigation water management, as the results are generally accurate enough using relatively few input parameters (Kool *et al.* 2014). However, similarly to the single K_c approach, this approach is empirical and pre-defined crop coefficients are usually site-specific (Ferreira *et al.* 2012). There is also a tendency to overestimate T when the soil is dry due to inclusion of some E_s in the calculation of K_e (Allen *et al.* 2005; Villalobos *et al.* 2013), or on days with high ET_o due to insufficient water uptake by the plant to meet the atmospheric demand, even under well-watered conditions as the result of high levels of stomatal control (Paço *et al.* 2012; Kool *et al.* 2014; Taylor *et al.* 2015). This is mainly attributed to the fact that crop coefficient models assume atmospheric demand-limited conditions and T in well-coupled crops, like most fruit tree orchards, is likely to be water supply limited, as seen in citrus (Taylor *et al.* 2015) and peaches (Paço *et al.* 2012) due to a strong stomatal regulation. Thus, models which are based on a stomatal conductance approach are likely to be more appropriate to accurately predict T and/or ET of fruit tree species.

2.5.3 Stomatal conductance approach

Stomatal conductance is most often described using mathematical expressions, which represent physical and physiological characteristics of the biological process being

studied (Damour *et al.* 2010). The most common models fall within two main categories, namely: (1) models applied at the leaf level, which include multiplicative models of environmental influences and models of stomatal behaviour; (2) models applied at the canopy level, which include those that are based on the Penman-Monteith resistance model (Leuning, 1990; Leuning, 1995; Rana and Katerji, 2000; Pereira *et al.* 2006; Damour *et al.* 2010). In both categories of models, stomatal conductance is estimated taking into account both canopy properties and meteorological conditions. Models applied at the leaf level may not be able to provide accurate estimations of T for an entire canopy due to the fact that changes in stomatal conductance are highly variable: (1) at the leaf level, due to changes in stomatal characteristics (stomatal density and pore length), different exposure of leaves to solar radiation due to shading by other leaves in a canopy and orientation of parts of an irregularly shaped leaf with respect to the solar beam, variations in water potential gradients as a result of internal resistances to water movement through the leaf, and fluctuations in the solute potentials of guard cells; and (2) at the canopy level, due to all the reasons described earlier, and as a result of the configuration of leaves within a plant canopy, where leaves may touch one another, and as a result, their individual boundary layers may overlap (Jarvis and McNaughton, 1986). The Jarvis-Stewart model is a clear example of stomatal conductance models applied at the leaf level, in which the g_s response is integrated to quantum flux density (Q_{FD} , $\mu E m^{-2} s^{-1}$), leaf temperature (T_l , °C), leaf-to-air vapour pressure deficit calculated at leaf temperature (VPD_l , kPa), ambient CO₂ concentration (C_a , ppm) and leaf water potential (ψ , MPa), according to the following equation (Jarvis, 1976):

$$g_s = f(Q_{FD})(T_l)(VPD_l)(C_a)(\psi) \quad (2.18)$$

Noting all the limitations with the use of stomatal conductance models applied at the leaf level, it is very important to consider modelling stomatal conductance at the canopy level, i.e. canopy conductance (g_c), in order to obtain more accurate estimates of whole-plant T. In this case, the effects of changes in the fluxes of heat and water vapour from all the individual leaves are likely to accumulate and lead to substantial changes in the saturation VPD around the leaves within the canopy (Jarvis and McNaughton, 1986). In order to predict these effects on T, the resultant changes in saturation VPD that will occur at the canopy level, as a result of the changes in

stomatal conductance should be estimated. With such consideration models of g_c were developed, which estimate an unweighted total of stomatal conductances of all the leaves within a canopy (Leuning *et al.* 1995; Whitehead, 1997; Wang and Leuning, 1998; Granier *et al.* 2000; Leuning *et al.* 2008; Whitley *et al.* 2009; Egea *et al.* 2011; Villalobos *et al.* 2013; Ding *et al.* 2014). The Penman-Monteith resistance model based on the “big-leaf” approach is a clear example of a model in which g_c is obtained by scaling-up measurements of g_s , conducted on individual leaves using a portable gas exchange device, to the canopy level using average leaf area index (LAI) measurements for the entire canopy (Whitehead, 1997).

In an attempt to provide direct estimates of crop ET, the Shuttleworth–Wallace model was developed, in which the crop ET is estimated using two distinct Penman-Monteith resistance equations, i.e. one for the crop (for estimation of T) and the other for the soil surface (for estimation of E_s) expressed as follows (Zhao *et al.* 2015):

$$E_s = \left[1 + \frac{R_s R_a}{R_c (R_s + R_a)} \right]^{-1} \frac{\Delta A + \left(\frac{\rho_a c_p \text{VPD} - \Delta r_a^s (R_n - G)}{r_a^a + r_a^s} \right)}{\Delta + \gamma \left(\frac{1 + r_s^s}{r_a^a + r_a^s} \right)} \quad (2.19)$$

$$T = \left[1 + \frac{R_c R_a}{R_s (R_c + R_a)} \right]^{-1} \frac{\Delta A + \left(\frac{\rho_a c_p \text{VPD} - \Delta r_a^c A_s}{r_a^a + r_a^c} \right)}{\Delta + \gamma \left(\frac{1 + r_s^c}{r_a^a + r_a^c} \right)} \quad (2.20)$$

where Δ is the slope of saturation vapour pressure curve (kPa K^{-1}); γ is psychrometric constant (kPa K^{-1}); r_s^c and r_a^c are bulk stomatal resistances of the canopy (estimated by inverting values of g_c modelled using the “big-leaf” approach) and boundary layer resistance (s m^{-1}), respectively; r_a^s and r_a^a are aerodynamic resistances from soil to canopy and from To reference height (s m^{-1}), respectively; r_s^s is soil surface resistance (s m^{-1}).

Penman-Monteith resistance models include climatic (R_n and VPD) and parametric variables (r_a^a and r_s^c) (Pereira *et al.* 2006; Zhao *et al.* 2015) which strongly influence modelling results. Vapour pressure deficit in particular must be measured very accurately and r_s^c must be precisely modelled for appropriate estimates of crop water use (Rana and Katerji, 1998). This has made the initial version of the Shuttleworth–

Wallace model hard to parameterize, and as a result, a simplified format of its representation was developed to estimate E_s using the Priestley–Taylor formula (Li *et al.* 2010):

$$E_s = \alpha_E \tau \frac{\Delta}{\lambda(\Delta + \gamma)} (R_n - G) \quad (2.21)$$

$$\begin{cases} \tau \leq \tau_c, \alpha_E = 1 \\ \tau > \tau_c, \alpha_E = \alpha - (\alpha - 1)(1 - \tau)/(1 - \tau_c) \end{cases} \quad (2.22)$$

where α_E is the coefficient of the Priestley–Taylor formula with relevance to light interception, τ_c and α is 0.55 and 1.3, respectively. The use of Priestley–Taylor formula has made the estimation of the E_s component relatively easier and more applicable using the Shuttleworth–Wallace model, because it requires more easily obtainable parameters and is valid for humid and sub-humid regions (Kool *et al.* 2014). However, the procedure does not account for variability of E_s due to changes in the wetted surface area and wetting frequency as affected by irrigation and rainfall events, which is crucial for accurate E_s predictions. While researchers have tried to simplify the formulation of E_s component of the Shuttleworth–Wallace model, nothing has been done to address the challenges of modelling the T component. The most critical point of the Penman-Monteith model for tall orchard crops is the estimation of r_s^c which is determined by inverting values of g_c modelled using the “big-leaf” approach. Thus, g_c should be modelled mechanistically. The problem is that g_c is estimated as a function of g_s measured on single leaves and average LAI measurements for the entire canopy, using the “big-leaf” approach, by scaling-up stomatal conductance from a leaf to canopy level, which is not trivial and an adequate solution has yet to be found, particularly for semi-arid environments. An improved method of estimating g_s was proposed to minimise this problem, in which the canopy is divided into various layers and g_s is estimated for each layer and weighted with the LAI for each layer using a multi-layer approach (Leuning *et al.* 1995), or in which the canopy is divided into two distinct layers of sunlight and shaded leaves using a “two-leaf” approach (Wang and Leuning, 1998; Ding *et al.* 2014). Either of the described methods may result in erroneous estimates of g_c due to the use of averaged g_s and LAI for each sub-layer to estimate g_c for the entire canopy.

In order to overcome such limitations, Villalobos *et al.* (2013) proposed a different approach, in which g_c is modelled directly using measurements of T . The approach used to predict g_c with the model of Villalobos *et al.* (2013) is based on the concept that canopy assimilation is proportional to radiation interception. This approach was found acceptable for well-coupled crops where the ratio of aerodynamic conductance (g_a) to g_c is generally sufficient high (Villalobos *et al.* 2000; Orgaz *et al.* 2007). Estimates of g_c are subsequently used to derive crop parameters (a and b), through a linear regression of $(f_{IPAR} \cdot R_s)/g_c$ against VPD, which are subsequently used for direct estimates of daily T (mm day^{-1}) using the following equation:

$$T = 37.08 \times 10^{-3} \frac{f_{IPAR} R_s}{a + b \text{ VPD}} \frac{\text{VPD}}{P_a} \quad (2.23)$$

where f_{IPAR} is the fraction of photosynthetically active radiation intercepted by the canopy (dimensionless), R_s is the total daily solar radiation ($\text{J m}^{-2} \text{ d}^{-1}$), P_a is the atmospheric pressure (kPa), VPD is vapour pressure deficit (kPa), the coefficient 37.08×10^{-3} incorporates the conversion of units for Joules of solar radiation to mol quanta and from mol to kg of H_2O , and a and b are the intercept and slope of the linear function relating $(f_{IPAR} \cdot R_s)/g_c$ to VPD.

Good estimates of T were obtained using this approach of modelling g_c , for a number of fruit tree species including apricots, citrus, olives, peaches and walnuts, and as a result, it can be concluded that when the required modelling parameters are adequately determined, this simple canopy conductance approach can be more accurate than the standard crop coefficient approach for the following reasons: (1) it requires fewer meteorological inputs; (2) it predicts that the increase in T slows down as VPD increases, which is an important aspect to model T in supply-limited fruit tree crops; (3) it provides more precise estimates of T , due to the fact that T is estimated directly without the inclusion of any E_s and using estimates of fractional intercepted photosynthetic active radiation, unlike T estimates using the dual K_c approach which contains some E_s when the soil is dry and estimates of fractional canopy cover are used for T predictions (Allen *et al.* 1998; Villalobos *et al.* 2013). To date, there are no studies reporting on parameterization and validation of the canopy conductance model of Villalobos *et al.* (2013) to estimate T of pecans or macadamias. This opens

opportunities to further extend the application of the canopy conductance model of Villalobos *et al.* (2013) to a wider range of fruit tree species.

2.6 CONCLUSIONS

Despite South Africa being a world-leading producer of pecans and macadamias, very little research has been conducted on water use of these crops. This may have implications for judicious irrigation scheduling and irrigation water management, as crop water use is highly variable depending on a number of factors including climate variability, making experimental results obtained elsewhere not locally applicable. In this study, available literature has been reviewed, from which a number of morphological, physiological and anatomical differences were identified between pecans, a deciduous, and macadamias, an evergreen tree nut species, which will impact crop response to changes in environmental conditions and the process of crop water use. Evergreen species have leaves with a longer life-span and smaller fluctuations of leaf water potentials, turgor pressure and leaf water content per unit of dry mass throughout the season, their leaves are usually thick and sclerophyllous or xeromorphous with higher leaf-specific conductivity rates (an index that measures the ability of the stem to supply water to leaves) as compared to deciduous species.

To date, there is only one study reporting the environmental control of transpiration in macadamia trees grown under controlled conditions of incident solar radiation, whilst there is almost a complete lack of information on the regulation of transpiration in pecan trees. The present study provides a detailed assessment on the environmental regulation of transpiration in field-grown pecan and macadamia trees, using two to three consecutive seasons of daily measured data. This knowledge will contribute to a deeper understanding of the regulation of water use in these tree nut crops, which is expected to vary between a deciduous and an evergreen species as the result of their morphological, physiological and anatomical differences.

The majority of research on water use of pecans has been conducted in the USA, under similar conditions of climate and irrigation system, which makes it difficult to extrapolate the reported experimental results to different conditions where pecan water use has not been measured. Similarly to pecans, the need to quantify

macadamia water use has also been identified as of primary importance, since there is only one study reporting daily water use of macadamias grown in Queensland, Australia. Thus, results from this present study will contribute to extended knowledge on water use for these tree nut crops, by providing an accurate quantification of crop evapotranspiration and its partitioning into soil evaporation and transpiration, using robust measurement techniques and modelling approaches.

Various models based on a single crop coefficient approach have been used to estimate water use of flood-irrigated pecans, grown under arid climatic conditions in the USA. The problem is that, the crop coefficient modelling approach is empirical and pre-defined crop factors are usually site-specific, which makes model evaluation crucial under a range of conditions. Unfortunately, none of these modelling approaches have been evaluated in production regions other than where they were developed, which may 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. This study evaluates the performance of a pecan-specific single crop coefficient model developed in the USA, and proposes an improved method which can be more easily transferred to a wider range of climates and orchard management practices. Macadamia-specific single crop coefficients have also been developed in this study to predict monthly evapotranspiration of this crop, offering great potential to quantify macadamia water use across various climatic conditions, as currently there are no crop coefficients available for macadamias. The single K_c modelling approach proved to be robust enough to accurately model crop ET on a monthly basis, but for shorter time-step predictions it may not be relevant, since it does not take into account changes in the wetted surface area and wetting frequency as affected by irrigation and rainfall events, which is crucial to accurately account for real time changes in soil evaporation. This can only be made possible using crop ET partitioning models, of which the dual K_c model of the FAO-56 is amongst the most relevant procedures, particularly for estimating the component of soil evaporation more accurately. Limitations of the dual K_c approach were, however, raised by researchers when estimating the component of transpiration of fruit tree species, as crop coefficient models assume atmospheric demand-limited conditions and transpiration in well-coupled crops, like most fruit tree orchards, is likely to be water

supply limited. This is probably the reason why, later on, researchers thought of developing a canopy conductance model which predicts daily transpiration of fruit trees directly, using estimates of fractional intercepted photosynthetic active radiation. This model has been successfully calibrated for selected fruit tree species, excluding pecans and macadamias. This study demonstrates the relevance of the canopy conductance model in comparison to the dual K_c model of the FAO-56 to estimate daily transpiration of pecan and macadamia trees more accurately.

CHAPTER 3: GENERAL MATERIALS AND METHODS

3.1 DESCRIPTION OF EXPERIMENTAL SITES

Field experiments for research in pecan trees were conducted in Cullinan (25° 35' 20.65" S and 28° 33' 31.90" E; approximately 1340 masl) and on the University of Pretoria's Hatfield Experimental Farm (25° 44' 55.88" S and 28° 16' 22.96" E; approximately 1370 masl), Gauteng province. Research trials in macadamia trees were conducted in White River (25° 21' 32.80" S and 31° 3' 34.44" E; approximately 765 masl), Mpumalanga province. All experimental sites were located within the summer rainfall area of South Africa. A detailed description of each experimental site is presented below.

3.1.1 Cullinan experimental site

The climate of Cullinan 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 mean daily temperatures varying between 9.7 and 21.2 °C (Schulze and Lynch, 2007). Field measurements were conducted in a mature 22 ha commercial, mixed cultivar pecan orchard (*Carya illinoensis*), planted in 1975 (34-year-old at the start of measurements, Figure 3.1). Measurements were conducted over three consecutive seasons from September 2009 until May 2012 in 'Choctaw' pecan trees on 'Barton' rootstocks. Trees were arranged triangularly in a 9 m x 9 m x 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 hours (equivalent to 31 mm) and was recorded using an in-line electrode and water meters, which were read every 2 weeks. 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 implemented, 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.



Figure 3.1 The mixed cultivar pecan orchard at Cullinan.

3.1.2 Hatfield experimental site

The climate of Hatfield, Pretoria is semi-arid subtropical, similar to that described earlier for Cullinan. Field measurements were conducted in a young 7-year-old, 3.0 ha mixed cultivar orchard, planted in 2006 (Figure 3.2). Measurements were conducted during the 2012/2013 and 2013/2014 seasons in ‘Wichita’ pecan trees on ‘Ukulinga’ rootstocks. Trees were arranged in hedgerows at two planting densities, either 10 m x 10 m spacing or 10 m x 5 m, along a N to S axis. Trees were pruned to a modified central leader prior to the start of the season, with an average tree height following pruning of 3 m and an average trunk diameter at 50 cm above the surface of 0.085 m.

The average yield in the 2012/2013 season was 0.24 t ha⁻¹ for the 10 m x 10 m spacing and 0.48 t ha⁻¹ for the 10 m x 5 m spacing, while in 2013/2014 it was 0.40 t ha⁻¹ for the 10 m x 10 m spacing and 0.80 t ha⁻¹ for the 10 m x 5 m spacing. The orchard was irrigated using three drip lines per tree, with drippers spaced 1.0 m apart and a delivery rate of 1.8 L h⁻¹, resulting in a wetted diameter of 0.8 – 1.0 m per dripper. Irrigation was typically scheduled once every six days for 6 to 10 hours (equivalent to 3 - 5 mm) and was recorded using water meters. The soil type was sandy clay loam and each tree was fertilized with 2 - 4 kg of Terra Nova organic fertilizer at the beginning of the season.



Figure 3.2 The mixed cultivar pecan orchard at Hatfield.

3.1.3 White River experimental site

The climate of the study site in White River is humid subtropical, with mean daily temperatures varying between 4.2 and 29.1 °C and an average annual rainfall of 722 mm (Schulze and Lynch, 2007). Field measurements in White River were conducted in a bearing 'Beaumont' macadamia orchard (*Macadamia integrifolia* X *Macadamia tetraphylla*) planted in 2005 on 'Beaumont' rootstock from October 2010 to October 2012 (Figure 3.3). Trees were arranged in hedgerows, with an 8 m x 4 m spacing (32 m² per tree) in a 34 ha block. Tree row orientation was along a N to S axis. The orchard

was irrigated using two drip lines per tree row, with drippers spaced 1.0 m apart and a delivery rate of 1.8 L.h⁻¹, resulting in a wetted diameter of 1.0 – 1.6 m per dripper. Irrigation was typically scheduled three to five times per day, almost every day (increasing from winter to summer). The average tree height throughout the measurement period was 5.0 m, with the average trunk diameter at 0.5 m increasing from 0.118 to 0.123 m over the two-year trial period. Average yield increased from 4.8 t ha⁻¹ in-shell in 2010/2011 season to 6.0 t ha⁻¹ in-shell in the 2011/2012 season. Trees were pruned to a modified central leader prior to the start of each season. The soil type was sandy loam to sandy clay loam. Inorganic fertigation was performed based on soil and leaf analyses.



Figure 3.3 The ‘Beaumont’ macadamia orchard in White River.

3.2 FIELD MEASUREMENTS

3.2.1 Fractional interception of photosynthetically active radiation by the canopy

Fractional interception of photosynthetically active radiation (f_{iPAR}) of six trees at each experimental site was measured every two to four weeks using a Decagon AccuPAR LP-80 ceptometer (Decagon Devices, Pullman, WA, USA). Sampling of PAR below

the canopy was conducted across and within the row (covering the total area allocated to one tree) at pre-determined 1 m intervals, whilst a full sun reading was taken in an open area next to the orchard. All measurements were taken between 12 and 2 pm, under clear sky conditions following the procedure described by Decagon Devices (2004). Monthly effective fractional cover ($f_{c\text{ eff}}$) of the orchard was estimated by averaging measurements of f_{IPAR} in each month, as a 1:1 relationship between measurements of f_{IPAR} and $f_{c\text{ eff}}$ determined using a grid method was found in young pecan and macadamia orchards (Figure 3.4).

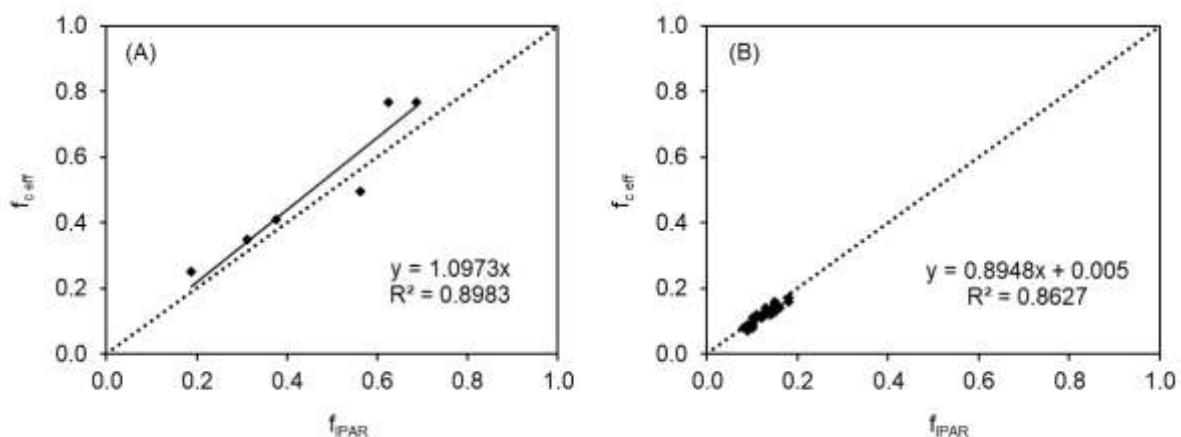


Figure 3.4 Relationship between measurements of fractional interception of photosynthetically active radiation (f_{IPAR}) and effective fractional cover ($f_{c\text{ eff}}$) in the young pecan orchard at Hatfield and young macadamia orchard in White River.

3.2.2 Meteorological measurements

Daily reference evapotranspiration (ET_o) and vapour pressure deficit (VPD) for the measurement period were calculated using the procedure described in FAO-56 (Allen *et al.* 1998) from weather data obtained from an automatic weather station (AWS) located on each farm, within 500 to 800 m of the orchards. The weather parameters recorded were wind speed, solar radiation, temperature, relative humidity and rainfall. Quality assessment and quality control of weather data obtained from all the AWS was performed according to the procedures described by Allen (2008). Quality of the data was found to be good and no corrections were necessary. The AWS at Cullinan was located on an open stretch of mown, rain-fed grass and was 50

m north of natural vegetation, which consisted of sparse trees (2-3 m tall) and grasslands. There were irrigated orchards within 500 m to the north-east. Under these fairly dry conditions, calculated ET_o is likely to be slightly overestimated, as compared to calculations made using weather data collected over a reference surface (Allen, 2008). The AWS at Hatfield and White River experimental sites was located above a rain-fed, short grass surface, with irrigated fields within 60 m (Figure 3.5). Under these conditions, ET_o is likely to be well-estimated (Allen, 2008).



Figure 3.5 Automatic weather station installed in the macadamia orchard at White River experimental site.

3.2.3 Soil water content measurements

Volumetric soil water content (θ) was measured using a TDR100 (Time-Domain Reflectometry) system (Campbell Scientific Inc., Logan, Utah, USA), installed in close proximity to the experimental trees in Cullinan and White River experimental sites (Figure 3.6A and B). Volumetric soil water content was recorded hourly using a TDR100 system connected to CR10X dataloggers (Campbell scientific Inc., Utah, Logan, USA) and six SDMX50 multiplexers in Cullinan and three SDMX50 multiplexers in White River.

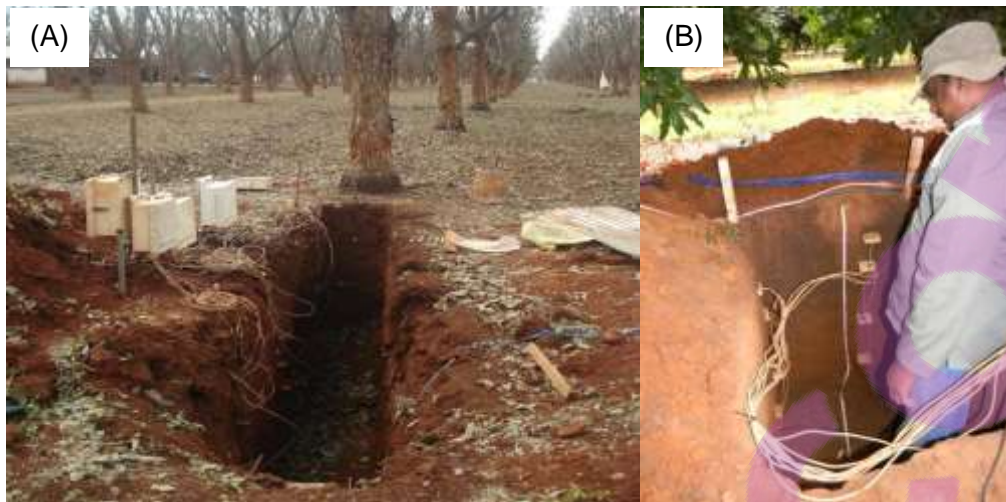


Figure 3.6 Installation of TDR100 soil water sensors at various depths and positions around a representative tree in the (A) pecan orchard in Cullinan and (B) macadamia orchard in White River.

In the pecan orchard a total of 48 CS610 TDR soil water sensors were installed up to 1.0 m below the soil surface (at depths of 0.15, 0.2, 0.4, 0.6, 0.8 and 1.0 m), at eight different positions in the orchard. Six of these profiles were within the tree row (three on each side of the tree, at 1.5 m, 3 m and 4 m from the tree trunk – Figure 3.7) and the remaining two profiles were located across the tree row (both within the work row on the west side of the tree row, at 1.5 m and 4 m from the tree trunk). This configuration accounted for variability in soil water content as influenced by different wetting and shading regimes, as well as root distribution and therefore tree water use. Volumetric soil water content was recorded hourly using a TDR100 system connected to CR10X datalogger (Campbell scientific Inc., Utah, Logan, USA) and six SDM50 multiplexers.

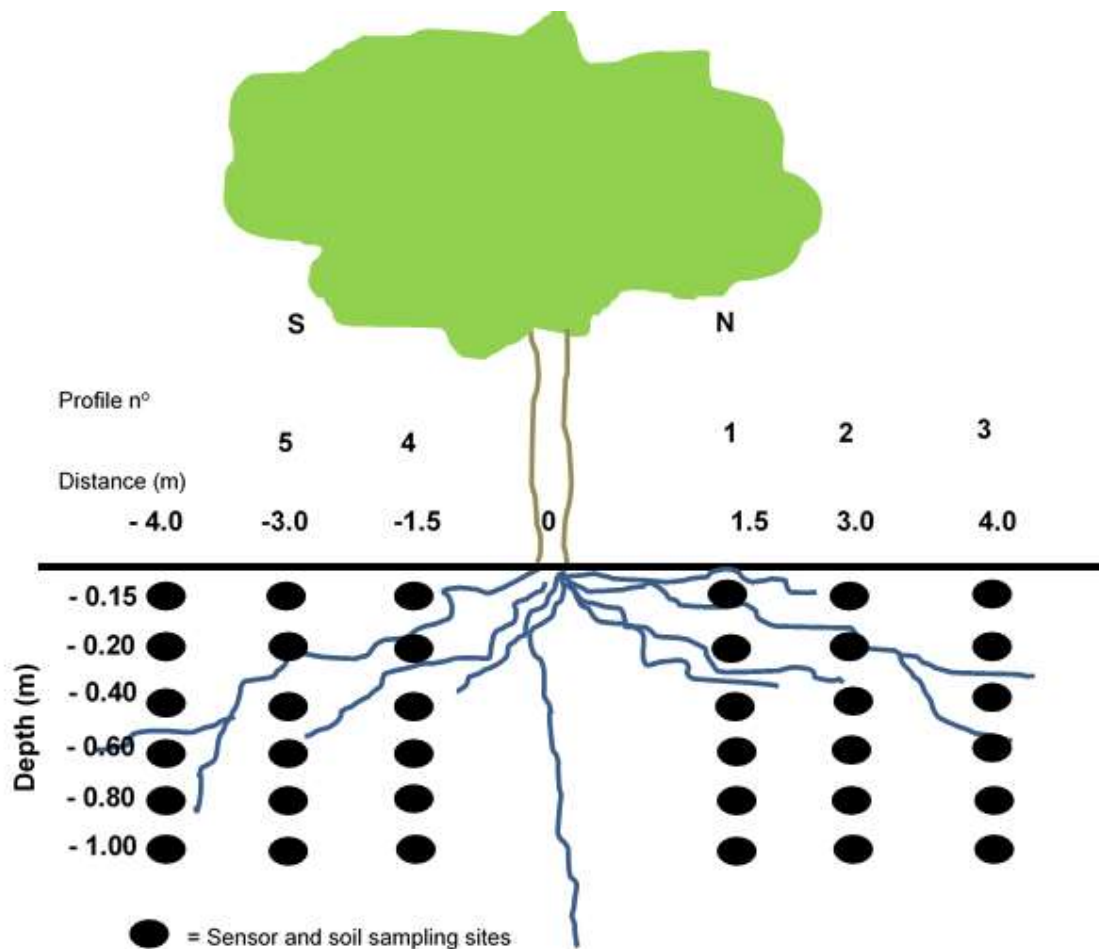


Figure 3.7 Placement of TDR probes in the pecan orchard at Cullinan site, to account for variability in wetting and shading within the area allocated to each tree, for measurements of volumetric soil water content.

In the macadamia orchard a total of 13 CS610 soil water sensors were installed up to 0.9 m below the soil surface (at depths of 0.15, 0.3, 0.6 and 0.9 m) at three locations within the orchard. The locations were selected as follows: (1) between the tree rows within the working row (Profile n° 1), (2) within the tree row directly underneath a dripper (a probe at 0.75 m was included in this position, as showed in Profile n° 2) and (3) within the tree row in between two drippers (Profile n° 3), as illustrated in Figure 3.8.

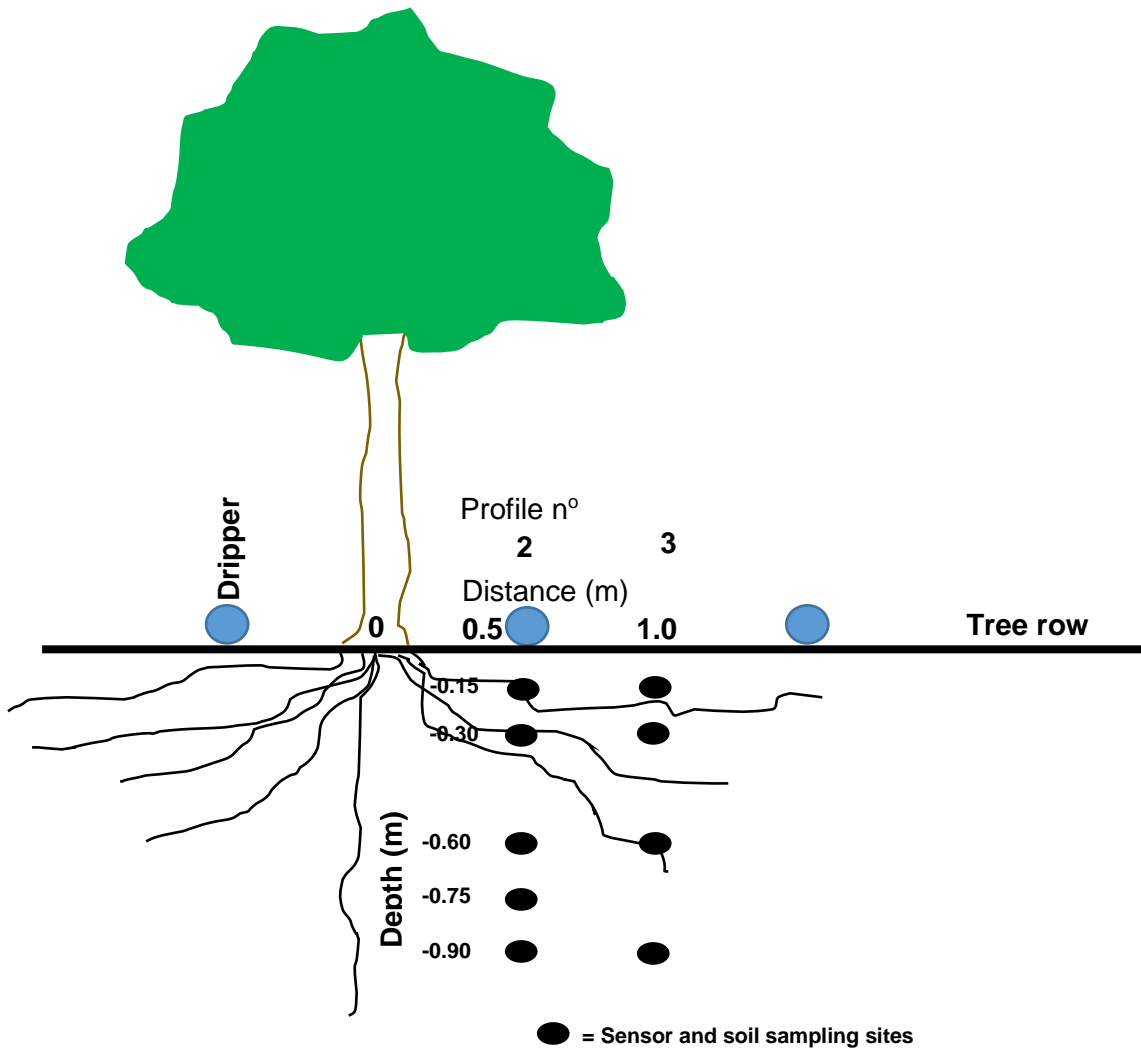


Figure 3.8 Placement of TDR probes in the macadamia orchard at White River site, to account for variability in wetting and shading within the area allocated to each tree, for measurements of volumetric soil water content.

In both experimental sites, a weighted average volumetric soil water content (θ) was calculated to represent average profile θ in the orchard and only the first 0.45 m θ was used in the data analysis of macadamia trees, as the active root zone of macadamias, which is composed by a dense mat of fibrous roots, is generally concentrated in the top 0.4 m of the soil profile (Firth *et al.* 2003). This dense clusters of roots is responsible for most of the nutrient and water absorption by macadamia roots (Stephenson and Trochoulias, 1994). For the pecan trees, on the other hand, θ measurements up to 1.0 m were considered, since their effective root zone can reach

up to 1.4 to 1.5 m deep depending on soil texture and position of the water table (Sorensen and Jones, 1999). During the installation of the TDR sensors, soil cores were collected in the various soil surface layers to determine soil texture. Soil cores from the top soil surface layer in the pecan orchard were collected at the various distances from the tree row in order to assess variations in root density and their influence on soil water content and E_s . Roots were washed out of the soil cores and collected on a fine mesh sieve, while precautions were taken to remove any debris or weeds. The roots were subsequently oven-dried at 65 °C for two days, and the dry mass was used to determine root density as the ratio between root dry mass and volume of the soil corer (40 cm³), as described by Hedley *et al.* (2010).

3.2.4 Irrigation scheduling monitoring

In the pecan orchard, irrigation was typically scheduled once every six days for 24 hours (equivalent to 31 mm) and was recorded using an in-line electrode and water meters, which were read every 2 weeks, while in the macadamia orchard it was typically scheduled three to five times per day, almost every day (increasing from winter to summer). Irrigation scheduling was monitored through soil water content measurements using a Time-Domain Reflectometry system. The allowable depletion was kept between 0 – 20% of plant available water throughout the experimental period. Seasonal cumulative water supply (irrigation plus rainfall) was above the atmospheric evaporative demand (represented by ET_o) and crop evapotranspiration in both experimental sites, as observed in Figures 3.9 for the 37-year-old pecan orchard during the 2011/12 season at Cullinan and 3.10 for the 6-year-old macadamia orchard during the 2011/12 season at White River.

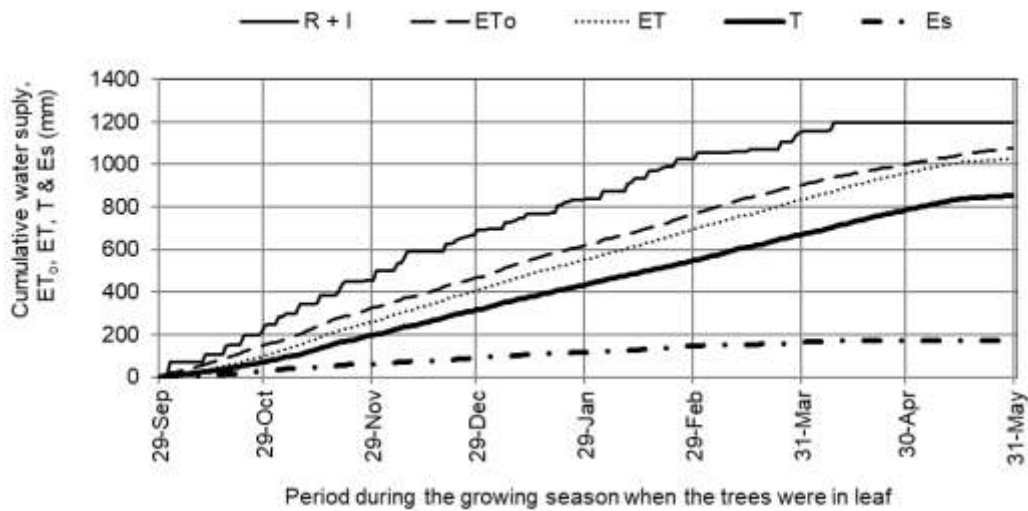


Figure 3.9 Cumulative water supply (rainfall – R plus irrigation – I) in comparison to grass reference evapotranspiration (ET_0) and crop water use (evapotranspiration – ET, transpiration – T and soil evaporation – E_s) for the 37-year-old pecan orchard during the 2011/2012 growing season at Cullinan.

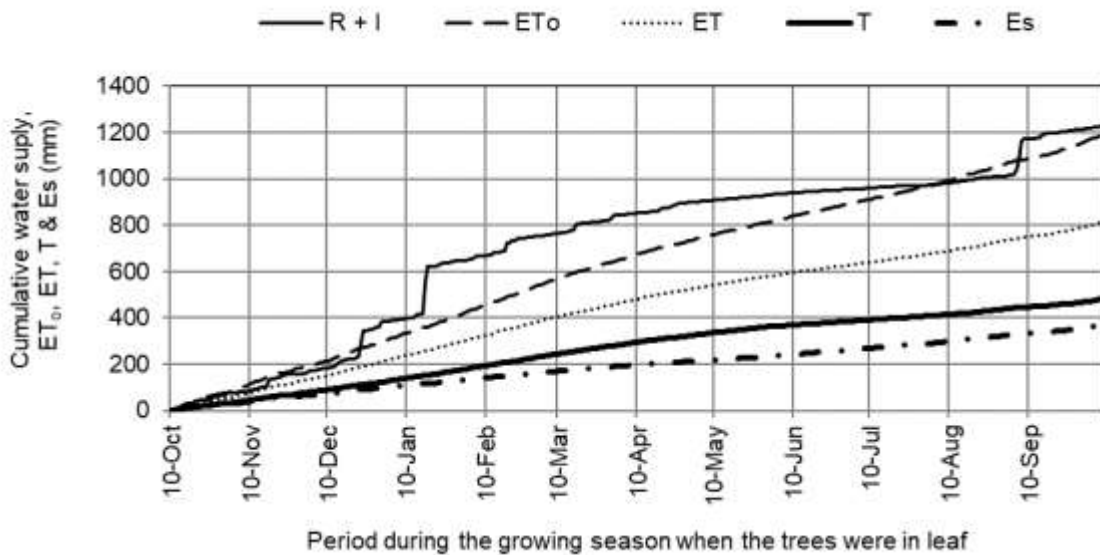


Figure 3.10 Cumulative water supply (rainfall – R plus irrigation – I) in comparison to grass reference evapotranspiration (ET_0) and crop water use (evapotranspiration – ET, transpiration – T and soil evaporation – E_s) for the 6-year-old macadamia orchard during the 2011/2012 growing season at White River.

3.2.5 Crop evapotranspiration measurements

An extended Open Path Eddy Covariance (OPEC) system (Campbell Scientific Inc., Logan, UT, USA) was installed in the pecan orchard at the Cullinan experimental site, at 1.5 m above the 14.5 m tall trees (Figure 3.11A) and in the macadamia orchard in White River at 1.2 m above the 5.0 m tall trees (Figure 3.11B). Micrometeorological variables measured included latent (λE), sensible heat (H) and soil heat (G) fluxes. These measurements were conducted for 32 consecutive days in February 2012 in the pecan orchard and for four to eight days during four different window periods (winter, spring, summer and autumn) in the macadamia orchard.



Figure 3.11 Position of the Open Path Eddy Covariance system on (A) scaffolding in the centre of the pecan orchard and (B) a lattice mast in the macadamia orchard.

The OPEC system consisted of a CR5000 datalogger and a CSAT three-dimensional sonic anemometer (Campbell Scientific Inc., Logan, UT, USA), a LI-COR LI-7500 open path infrared gas analyser (LI-COR Inc., Lincoln, NE, USA) and a Vaisala HMP45C temperature and humidity sensor (Vaisala Oyj, Vantaa, Finland) which were sampled at a frequency of 10 Hz. Net radiation (R_n) was measured using an NR-LITE net radiometer (Kipp and Zonen, Delft, The Netherlands) and soil heat flux (G) was

measured with two Hukseflux HFP01 soil heat flux plates (Hukseflux Thermal Sensors, Delft, The Netherlands) arranged in parallel with two TCAV-L soil temperature averaging probes (Campbell Scientific Inc., Logan, UT, USA) at depths of 20 and 60 mm, which were used to calculate the heat stored above the plates. Accuracy of the R_n measurements were compared against R_n estimated using standard equations (Allen *et al.* 1998) based on solar radiation from an AWS located at the site (Allen *et al.* 2011a). Volumetric soil water content in the first 60 mm of the soil surface was measured using a Time-Domain Reflectometry system (CS616, Campbell Scientific Inc., Logan, UT, USA). These sensors were connected to a CR23X datalogger (Campbell Scientific Inc., Logan, UT, USA) and measurements were performed at 10 Hz frequency and averages obtained every 30 minutes. The quality of the ET data was assessed according to the procedure described by Allen *et al.* (2011a) and erroneous data was filtered from the data set. The surface energy balance closure was assessed following the procedure described by Twine *et al.* (2000). The consistency in energy balance closure was 85% (lack of closure was 15%) in the pecan orchard, while in the macadamia orchard it fluctuated between 65 and 90% (lack of closure was 10 to 35%). The data showing energy balance closure less than 70% (considered inadequate in most agricultural applications, Foken, 2008) was corrected using the Bowen ratio method and only corrected data with energy balance closure varying between 85 and 90% was used for analysis. The surface energy balance closure in the pecan and macadamia orchards are provided in Figures 3.12 and 3.13, respectively.

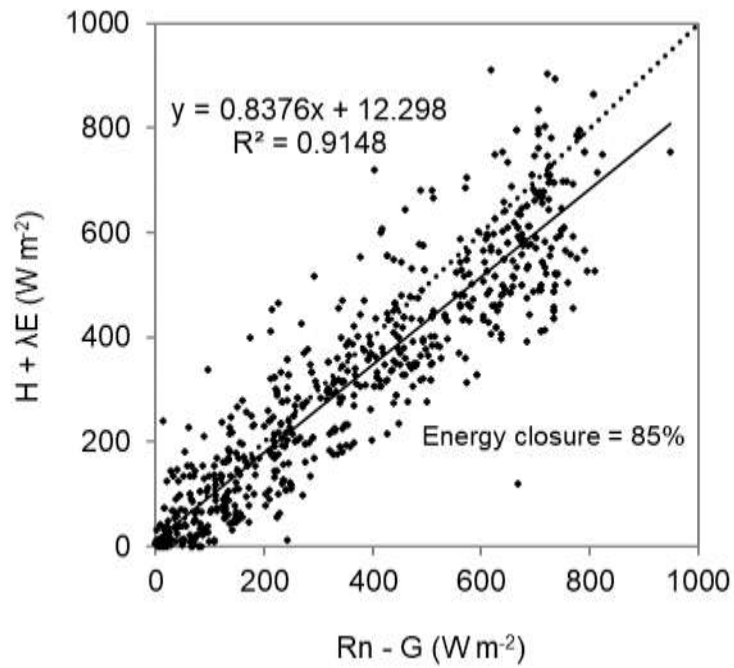


Figure 3.12 Surface energy balance closure for the mature pecan orchard at Cullinan during February 2012. Data are paired 30 min averages. The 1:1 line (dotted line) is provided together with the regression equation and coefficient of determination for the best-fit line through the data.

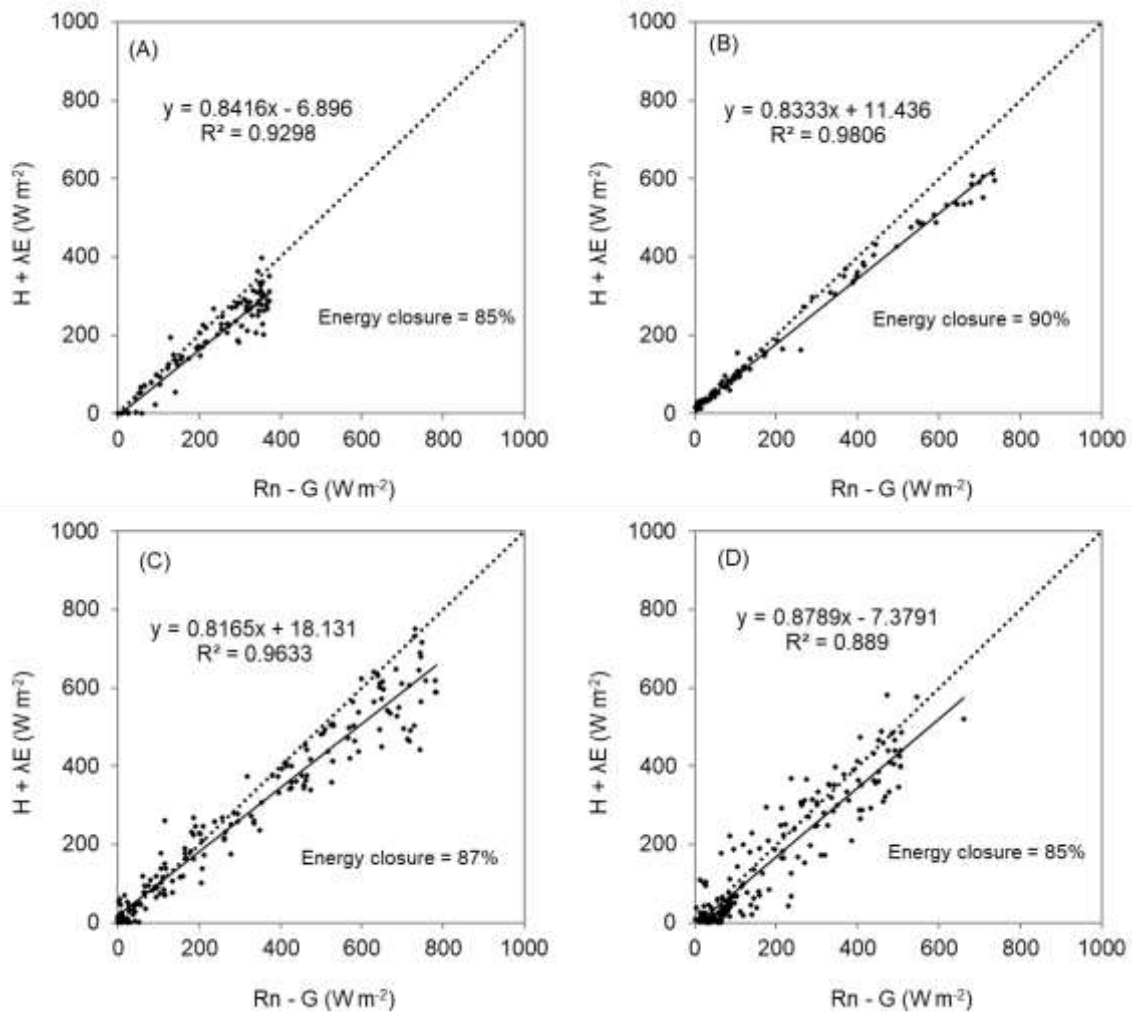


Figure 3.13 The surface energy balance closure for the macadamia orchard during (A) winter, (B) spring, (C) summer and (D) autumn window periods of measurements. Data are paired 30 min averages. The 1:1 line (dotted line) is provided together with the regression equation and coefficient of determination for the best-fit line through the data.

3.2.6 Soil evaporation measurements

Soil evaporation (E_s) measurements were conducted using micro-lysimeters, which were made of 3 mm-thick PVC pipe. They were 100 mm deep and had an internal diameter of 80 mm. Each micro-lysimeter was equipped with one external cylinder, made of 5 mm-thick PVC pipe, which was 100 mm in diameter and 100 mm in depth (Figure 3.14). The external cylinders were placed at fixed positions, across and along the tree rows to account for variability in wetting and shading within the area allocated

to each tree, and for the presence of any ground cover, whilst the internal cylinders were replaced with soil cores extracted from homogenous areas within the orchard.



Figure 3.14 Micro-lysimeters used for soil evaporation measurements in 'Beaumont' macadamia orchard at White River experimental site.

At the Cullinan experimental site, E_s was measured using 12 micro-lysimeters for 10 days during February to March 2012, when $f_{c\text{ eff}}$ was 82%. The measurement period comprised one rainfall and two irrigation events. At the Hatfield experimental site, seven micro-lysimeters were used to measure E_s of the 7-year-old drip irrigated pecan orchard, for 12 days during April 2013, when $f_{c\text{ eff}}$ was 12%. While at the White River experimental site nine micro-lysimeters were used to measure E_s for three days during winter (30 June to 2 July 2011) when $f_{c\text{ eff}}$ was 40%, summer (25 to 27 January 2012) when $f_{c\text{ eff}}$ was 80% and autumn (17 to 19 April 2012) when $f_{c\text{ eff}}$ was 70%.

The procedure for E_s measurements varied according to the frequency of irrigation events. In the drip irrigated macadamia orchard, extraction of cores from the top soil

layer was typically done an hour after the end of an irrigation event (which typically occurred 3 – 5 times per day), and renewal as well as weighing of these cores was performed every hour from 8 am to 5 pm. In the drip irrigated young pecan orchard, due to a longer irrigation interval (typically once per week), extraction of core samples was conducted from the day after a rainfall or irrigation event, and renewal followed weighing of these cores was performed every two hours within the first 24 hours and daily thereafter (Daamen *et al.* 1993). The same procedure of E_s measurements was followed in the micro-sprinkler irrigated mature pecan orchard where similar irrigation frequencies were conducted. Daily mass loss was calculated as the sum of hourly mass loss from 8 am of each day to 8 am of the next day. The rate of E_s from each micro-lysimeter was calculated as the mass loss between measurements divided by the surface area of the micro-lysimeter (50.27 cm^2). Soil evaporation from the area allocated for one tree was calculated as a weighted (proportion of each specific area from the total area allocated to one tree, multiplied by the specific soil evaporation rate) average of the wetted and shaded areas represented by all micro-lysimeters, as illustrated in Figure 3.15 for the pecan orchard at Cullinan (areas 1 to 12), Figure 3.16 for the pecan orchard at Hatfield (areas 1 to 7) and Figure 3.17 for the macadamia orchard at White River (areas 1 to 9).

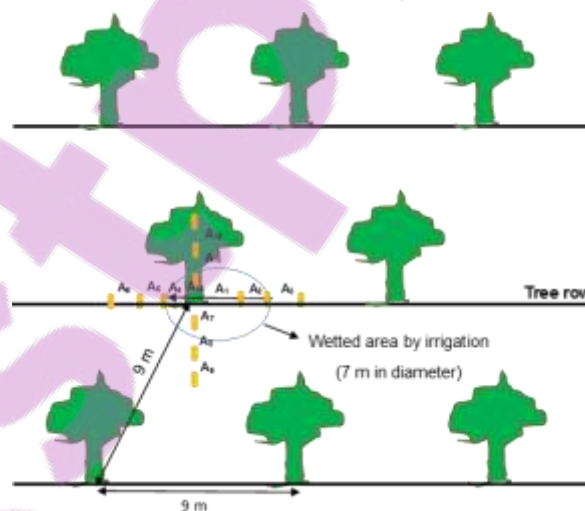


Figure 3.15 Placement of micro-lysimeters in the mature pecan orchard at Cullinan site for measurements of soil evaporation. A_1 to A_{12} represent different wetted and shaded soil surface areas within the ground area allocated to one tree.

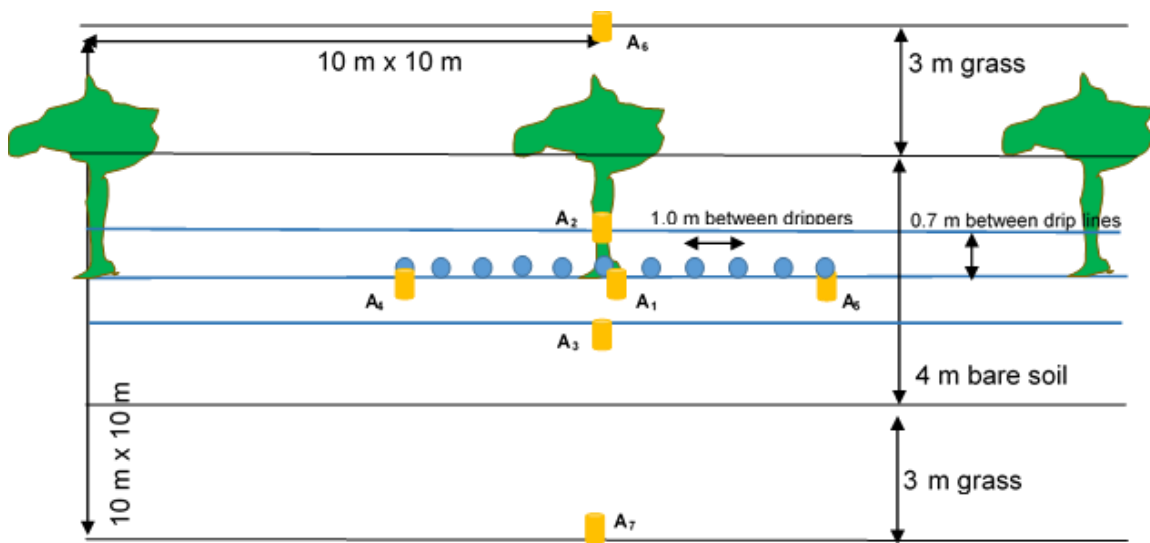


Figure 3.16 Placement of micro-lysimeters in the young pecan orchard at Hatfield site for measurements of soil evaporation. A₁ to A₇ represent different wetted and shaded soil surface areas within the ground area allocated to one tree.

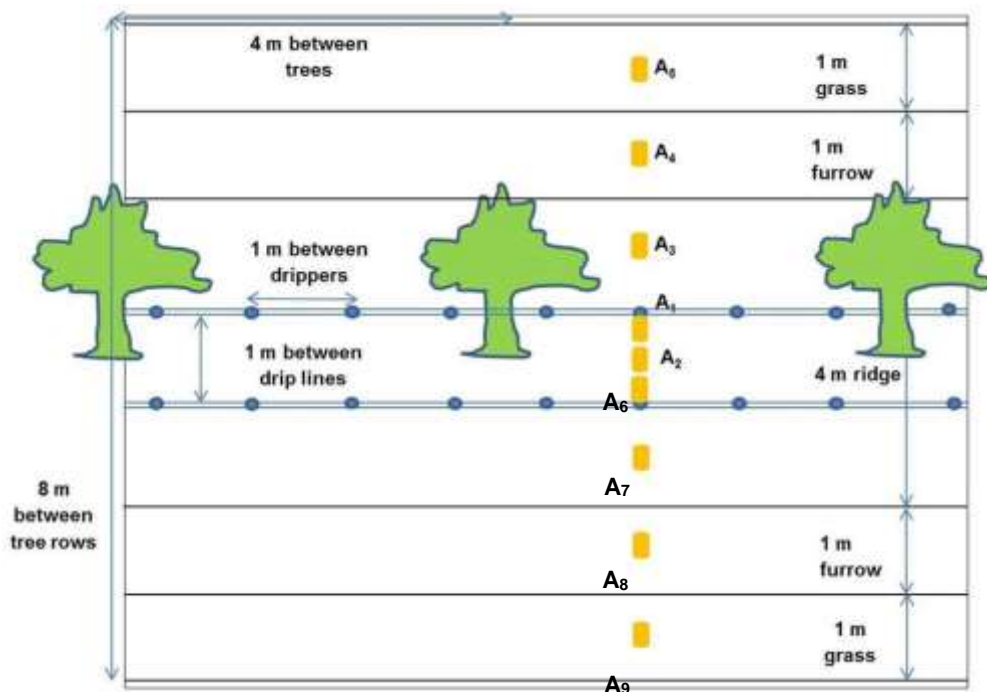


Figure 3.17 Placement of micro-lysimeters in the macadamia orchard at White River site for measurements of soil evaporation. A₁ to A₉ represent different wetted and shaded soil surface areas within the ground area allocated to one tree.

3.2.7 Measurements and calibration of sap flow

Sap flow measurements were performed using the heat ratio method (HRM), as described by Burgess *et al.* (2001) and Taylor *et al.* (2015) on two selected ‘Choctaw’ pecan trees at Cullinan, four selected ‘Wichita’ pecan trees at Hatfield (two trees planted at 10 m x 10 m and the other two planted at 10 m x 5 m) and five selected ‘Beaumont’ macadamia trees at White River experimental site. Measurements were conducted during the period when the trees were in leaf (September to May for pecans and June to May for macadamias). Three to four heat pulse probe sets were installed in each tree, each consisting of a 1.8 mm stainless steel heater probe and two Type-T copper-constantan thermocouples embedded in 2 mm outside-diameter PTFE tubing, placed equidistantly up and down stream of the heater probe at a distance of 0.5 cm (Figure 3.18).



Figure 3.18 Heat pulse velocity system measuring sap flow in ‘Beaumont’ macadamia trees during the 2010 – 2012 growing period at the White River experimental site.

In order to account for the radial variation in sap flux within the conducting sapwood, thermocouples were inserted at different depths in each tree trunk (Table 3.1). Probes were inserted in the trunk 0.5 m above the soil surface and were equally spaced and randomly arranged around the trunk.

Table 3.1 Details of the trees selected for sap flow measurements in the pecan and macadamia orchards.

Orchard	Tree No.	Stem Diameter (mm)	Bark Thickness (mm)	Probe Depths (mm)
37-year-old pecans	1	374	10	10, 30, 45, 60
	2	394	10	10, 30, 45, 60
7-year-old pecans	1	10	5	12, 25, 35
	2	8	5	12, 20, 30
	3	7	5	12, 20, 30
	4	8	5	12, 25, 35
6-year-old macadamias	1	131	4	10, 20, 35, 55
	2	112	4	10, 20, 30, 40
	3	111	4	10, 20, 30, 40
	4	118	4	10, 20, 30, 45
	5	119	4	10, 20, 30, 45

The HRM measured the ratio of the increase in temperature, following the release of a pulse of heat, at points equidistant downstream and upstream from a line heater. Thereafter, heat pulse velocities (V_h , $m\ s^{-1}$) were calculated for each probe set, following the procedure described by Burgess *et al.* (2001):

$$V_h = \frac{D_{ax}}{x} \ln \left(\frac{\Delta T_{down}}{\Delta T_{up}} \right) \quad (3.1)$$

where D_{ax} ($m^2\ s^{-1}$) is axial thermal diffusivity of the sapwood, x (m) is the distance between heat source (heater) and temperature sensors, and ΔT_{down} and ΔT_{up} are the increases in temperature (relative to ambient) at equidistant points from the heater.

The V_h data was automatically logged on an hourly basis using a CR10X datalogger and an AM16/32B multiplexer (Campbell Scientific Ltd, Logan, UT, USA). The data

was subsequently adjusted for systematic underestimation of sap flow rates caused by wounding, using appropriate wound correction coefficients, following the numerical model developed by Burgess *et al.* (2001). Corrected heat pulse velocities (V_c , m s^{-1}) were subsequently used to determine sap velocities (V_s , m s^{-1}) by measuring the fractions of sap and wood in xylem and accounting for their differing densities and specific heat capacities (Barret *et al.* 1995):

$$V_s = \frac{V_c \rho_d (c_d + MC c_w)}{\rho c_w} \quad (3.2)$$

Volumetric flow for an individual probe was calculated as the product of sap velocity (V_s) and its respective cross-sectional area of conducting sapwood. Integration of sap flux measurements by individual probes to obtain the whole-stem sap flux (Q) was performed following the method of weighted average of heat pulse velocity with depth, as described by Hatton *et al.* (1990):

$$Q = \pi [r_1^2 v_1 + (r_2^2 - r_1^2) v_2 + (r_3^2 - r_2^2) v_3 + (r_4^2 - r_3^2) v_4] \quad (3.3)$$

where v_k is the heat pulse velocity measured by probe k placed between radii r_{k-1} and r_k . The presence of heartwood, seen as wood discolouration, was determined by taking wood cores with an incremental borer. Integrated volumetric sap flow of the individual trees (L day^{-1}) was converted to whole-tree transpiration (T , mm day^{-1}) using the ground area allocated to each tree in the orchard i.e. 70.2 m^2 for the 37-year-old pecans, 100 m^2 for the 7-year-old pecans spaced at $10 \text{ m} \times 10 \text{ m}$, 50 m^2 for the 7-year-old pecans spaced at $10 \text{ m} \times 5 \text{ m}$ and 32 m^2 for the macadamias. Transpiration of the orchard was calculated as a weighted average of sampled trees, based on a stem circumference survey at the start of the study (Taylor *et al.* 2015). Transpiration determined through sap flow measurements was calibrated against T estimated as the residual of simultaneous measurements of ET and E_s conducted in the mature pecan orchard at the study site in February 2012 and in the macadamia orchard for three days during winter, summer and autumn, using an apparent wound width of 0.72 cm for pecans and 0.62 for macadamias (Figure 3.19A and B).

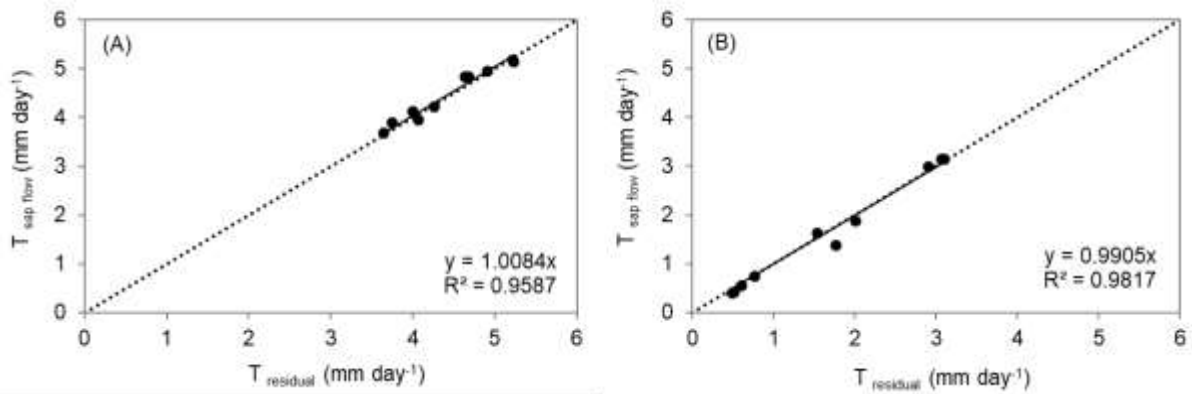


Figure 3.19 Comparison between transpiration estimated as the difference between simultaneous measurements of crop evapotranspiration and soil evaporation (T_{residual}) and calibrated sap flow measurements ($T_{\text{sap flow}}$) conducted (A) in the mature pecan orchard at Cullinan in February 2012 and (B) in the macadamia orchard at White River for three days during winter, summer and autumn seasons. The dotted line is the 1:1 line.

Similar calibrations of sap flow measurements have been performed by Köstner *et al.* (1992), Conceição and Ferreira (2009), Poblete-Echeverría *et al.* (2012), Taylor *et al.* (2013) and Taylor *et al.* (2015). The same trees selected for sap flow measurements were used for the duration of the trial, but probes were repositioned each year to account for radial expansion of the trunk and to minimise the impact of wounding on measurements.

CHAPTER 4: ENVIRONMENTAL CONTROL OF TRANSPIRATION IN IRRIGATED PECAN AND MACADAMIA TREES

4.1 INTRODUCTION

Understanding the driving factors for transpiration is a key aspect contributing to the identification of the most appropriate modelling approaches to estimate crop water use. The environmental control of transpiration (T) in fruit tree species has received little attention to date (Jarvis, 1985; Higgins *et al.* 1992; Carr, 2012a and 2012b; Carr, 2013), with the limited information that is available focusing mostly on environmental regulation of T in citrus and olives (Fernández *et al.* 1997; Moriana *et al.* 2002; Nicolás *et al.* 2008). In general, strong stomatal control over T has been demonstrated in these species, with vapour pressure deficit (VPD) being the dominant regulator of canopy conductance (Oguntunde *et al.* 2007; Nicolás *et al.* 2008; Rousseaux *et al.* 2009; Marin and Angelocci, 2011). These studies have mostly focused on evaluating the effect of an environmental variable on T, at different levels of another variable, using a similar approach to that employed for forest tree species (Wullschleger *et al.* 2000). This approach helps to understand the response of the dependent variable to an interaction between predictor variables, but does not provide a complete picture of their relationship. A more complete view of possible causal relationships between variables can be provided by estimating the conditional quantiles of a response variable distribution through a series of regression analyses (Koenker and Hallock, 2001; Cade and Noon, 2003). The applicability of quantile regression analysis was first introduced in the field of economics, and only more recently has it begun to be used in ecology and soil sciences (Cade *et al.* 1999; Mills *et al.* 2006; Mills *et al.* 2009). Using this type of analysis to evaluate the dependency of T on changes in environmental variables would not only provide a more detailed insight on their existent relationship, but would also help establish thresholds of these variables, above which stomata exert control over T. These thresholds have only been established for vapour pressure deficit (VPD = 1.5 kPa) on macadamia trees grown under controlled conditions in a gas exchange chamber (Lloyd, 1991), which may not be entirely representative of field conditions.

Whilst there is evidence of a strong stomatal regulation over T in evergreen fruit tree species, information on the regulation of T in deciduous species is almost completely non-existent (Pretorius and Wand, 2003; Gruia *et al.* 2011). The only study that is available in which direct comparisons of environmental regulation of T were made between selected evergreen (olive) and deciduous (almond, apple, fig, peach and pear) fruit tree species was conducted under controlled environmental conditions in a glasshouse of which results might differ from field growing conditions (Higgins *et al.* 1992). Evergreen fruit tree species generally have leaves with a longer life-span and smaller fluctuations of leaf water potentials, turgor pressure and leaf water content per unit of dry mass throughout the season, than leaves from deciduous species (Sobrado, 1986; Sobrado, 1991). Leaves of evergreen species are also usually thick and sclerophyllous or xeromorphous (Sobrado, 1986; Schaffer *et al.* 1994; Syvertsen *et al.* 1995; Chartzoulakis *et al.* 1999; Carr, 2012a; Carr, 2012b), whilst deciduous species have thin, mesophytic leaves (Sobrado, 1986; Andersen, 1994; Qi *et al.* 2003). Such morphological and physiological differences between evergreen and deciduous species, as well as differences in their climatic adaptability might result in contrasting crop responses to environmental variability. The available information on pecan water use research has mostly focused on measurement and modelling of crop evapotranspiration in arid regions of the USA, where pecans are generally flood irrigated (Miyamoto, 1983; Sammis *et al.* 2004; Wang *et al.* 2007; Samani *et al.* 2009; Samani *et al.* 2011), making it difficult to infer how much water was effectively used for T or how changes in T were affected by different environmental factors. This is important as T directly relates to the process of photosynthesis and therefore carbon assimilation. The situation is even more dire for macadamias, as there is almost a complete lack of information on either crop evapotranspiration or T measurement and modelling, particularly under field conditions (Stephenson *et al.* 2003; Carr, 2012a).

According to Jarvis (1985), T of a crop is considered to be made up of an imposed component driven by VPD and regulated by canopy conductance, and an equilibrium component driven by the receipt of net radiation. The role of each component in the regulation of T will depend on the degree of coupling between the leaves of an entire canopy and the atmosphere overhead, which is termed the decoupling coefficient, represented by the Ω symbol (Jarvis and Mcnaughton, 1986). The Ω coefficient varies from close to unity (poor coupling to the atmosphere) to close to zero (tight coupling

to the atmosphere), depending largely on leaf width, crop height and aerodynamic roughness of the crop (Jarvis, 1985). In poorly-coupled crops (mostly short or broad-leaved crops such as rhubarb, cucumber, bean, strawberry, tomato and grape vine), with an Ω coefficient varying between 0.5 and 0.9, T is considered to be made up of an equilibrium component, driven by the receipt of net radiation. In contrast, in well-coupled crops (mostly tall rough horticultural crops, such as orchards, with Ω of 0.1 to 0.2 or short narrow-leaved crops such as asparagus with Ω of 0.1) T consists of an imposed component, driven by VPD and regulated by stomatal conductance (Jarvis, 1985; Jarvis and McNaughton, 1986). The typical values of Ω for pecans and macadamias are unknown, which would provide insight into the role of stomata and VPD in controlling T.

It was hypothesized that as with most tall horticultural crops, T normalized for canopy size (T_c) of pecans and macadamias would be well-coupled to the atmosphere, and therefore T_c would be primarily driven by VPD and regulated by stomata. It was expected that increasing stomatal regulation of T_c in these crops at increasing VPD, would result in a maximum rate of T_c being reached that would not increase any further with increasing VPD. It was also hypothesized that macadamias would be able to restrict T_c more rapidly as VPD increased, due to the presence of morphological and physiological attributes which favour drought tolerance. This would result in lower T_c rates on a daily and seasonal basis for macadamias as compared to pecan trees, when normalised for canopy size. However, under relatively low levels of VPD pecans would transpire at higher rates, as compared to macadamias, due to the presence of larger sapwood areas, which would lead to higher canopy conductances. Such responses of T_c to atmospheric variability would not be evident by a simple day-to-day comparison between the dependant and the independent variables. An analysis of the variability of T_c in response to the changing condition of an atmospheric variable would therefore be required to assess the atmospheric thresholds imposing upper limits on T_c . In order to test these hypotheses, the following objectives were formulated: (1) to determine the Ω coefficient for irrigated pecan and macadamia trees grown under field conditions; (2) to compare day-to-day changes of T_c between pecan and macadamia trees in response to the atmospheric variability throughout the growing season; (3) to evaluate the response of T_c of these crops to different individual environmental

variables using a segmented quantile regression approach; and (4) to study the interactive effect of the most important atmospheric variables controlling T_c .

4.2 MATERIALS AND METHODS

4.2.1 Calculation of canopy and aerodynamic conductances and the decoupling coefficient

Daytime mean values of bulk canopy conductance (g_c , m s^{-1}) were calculated by inverting the imposed evaporation equation (Orgaz *et al.* 2007; Villalobos *et al.* 2013), using sap flow data measured in the 37-year-old pecan orchard and 6-year-old macadamia orchard:

$$g_c = \frac{TP_a}{VPD} \quad (4.1)$$

where P_a is atmospheric pressure (Pa). Mean daytime values of whole-tree transpiration (T , m s^{-1}) were obtained by dividing total T by daytime length (s) and vapour pressure deficit (VPD, Pa) was averaged for the daytime period. Equation 4.1 assumes that leaf temperature (T_l) equals air temperature (T_a), which is a fair assumption for full-irrigated orchard crops, since $T_l - T_a$ is significantly lower as compared to that of partially irrigated orchards (Andrews *et al.* 1992).

Values of g_c (m s^{-1}) were subsequently used to calculate daytime aerodynamic conductance (g_a , m s^{-1}), through the inversion of the Penman-Monteith equation (Kumagai *et al.* 2004):

$$g_a = \frac{g_c \left(\frac{\Delta}{\gamma} \beta - 1 \right) \lambda \rho T \gamma}{\lambda \rho T \gamma - g_c \rho_a c_p \delta e} \quad (4.2)$$

where Δ is the rate of change of saturation water vapour pressure with temperature (Pa K^{-1}), γ is the psychrometric constant (66.5 Pa K^{-1}), β is the Bowen ratio determined as the ratio between measured sensible heat flux and latent heat flux, λ is the latent heat of vaporization of water (J kg^{-1}), ρ is the density of water (1000 kg m^{-3}), T is whole-

tree transpiration (m s^{-1}), ρ_a is the density of dry air (kg m^{-3}), c_p is the specific heat of air at constant pressure ($\text{J kg}^{-1} \text{K}^{-1}$) and ζ_e is above-canopy atmospheric humidity deficit (Pa). For aerodynamically rough vegetation as expected from tall orchard crops, ζ_e can approximate VPD (Schafer *et al.* 2000), and as a result, VPD measured using an automatic weather station was used for estimation of g_a in this study.

Daytime values of the decoupling coefficient (Ω), which expresses the relative sensitivity of T to a marginal change in stomatal conductance, were calculated according to Jarvis and McNaughton (1986):

$$\Omega = \frac{[1+(\Delta/\theta)]}{[1+(\Delta/\theta)+(g_a/g_c)]} \quad (4.3)$$

Daily averages of Ω were obtained by averaging hourly daytime Ω values.

4.2.2 Sensitivity analysis of transpiration to variations in environmental factors

In order to assess the environmental control of T regardless of the effect of changes in canopy growth, whole-tree T was normalized using crown areas estimated from effective fractional cover and total ground area allocated to one tree in order to obtain canopy transpiration normalized for canopy size (T_c), following a similar approach proposed by Larsen *et al.* (1989), Wullschlegel *et al.* (2000) and Orgaz *et al.* (2007) for forest and fruit tree species. The dependency of T_c on individual environmental factors (vapour pressure deficit - VPD, solar radiation - R_s , mean air temperature - T_a and volumetric soil water content - θ) was analysed in various portions of the distribution of T_c (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9 quantiles - T), using a segmented, non-linear quantile regression approach. The variable VPD was chosen because vapor pressure difference between the leaf and the atmosphere is the principal atmospheric determinant of transpiration (Lloyd *et al.* 1991; Higgins *et al.* 1992; Rousseaux *et al.* 2009; Marin and Angelocci, 2011). Atmospheric variables such as wind speed and air temperature measured at 2 m height using an automatic weather station were chosen for analysis in this study, because this data is most often available, and therefore it can be easily accessible by growers for the purposes of modelling crop water use. A non-linear correlative approach was used due to the

heteroskedastic characteristics of the data sets (existence of multiple variances along the different portions of the distribution of T_c).

For pecan trees, a total of 960 observations (measurements of T_c from two experimental trees during two seasons of measurements of 240 days each) were used for evaluation of the dependency of T_c on VPD, R_s and T_a , whilst for the dependency of T_c on θ a total of 480 observations were used (corresponding to two monitoring trees, during one season of measurements). For macadamia trees, a total of 1800 observations (measurements of T_c from five experimental trees during one season - 365 days) were used to evaluate the dependency of T_c on VPD, R_s and T_a , while for the dependency of T_c on θ a total of 900 observations were used (corresponding to three monitoring trees in close proximity to the Time-Domain Reflectometry system for measuring θ). The consistency of the dependency of T_c on different environmental factors was verified using measured data obtained from an independent season of measurements.

The range of observations for each environmental variable was organized in an ascending order based on the independent variable, and subsequently divided into a number of classes of equal size (Mills *et al.* 2006). The total number of observations of the independent variable in each subset was used to calculate the T-th percentile of values in the range exclusively, following the equation below (Mendenhall *et al.* 2003):

$$R = T (N + 1) \tag{4.4}$$

where R is the rank of the T-th percentile, T is the desired percentile and N is the number of observations within each subset. When R was not an integer, the T-th percentile was computed by interpolation (Mendenhall *et al.* 2003).

The best polynomial function was then fit to the subset of observations for each quantile. The curve with the lowest degree order, not significantly different from curves with higher degree orders, was selected. Fitting of the best curve was done with the aid of statistical parameters such as coefficient of determination (R^2) and confidence intervals (CI) and their significant differences were assessed using the Fisher r-to-z

transformation included in the Statistical Analysis Software (SAS Institute Inc., 2011). The same statistical procedure was used to identify the most extreme quantile ($T = 0.9$), in order to minimize possible effects of outliers in the data sets (Cade *et al.* 1999). The multiple rates of change of T_c as influenced by individual environmental factors was estimated, from the minimum to the maximum response, by calculating the change rate of the dependant variable per unit increase in the independent variable (Cade and Noon, 2003).

After determining how individual environmental factors influence T_c , the response of T_c to the atmospheric evaporative demand (represented by ET_o) was evaluated at all possible combinations of relatively low and high levels of the most important atmospheric variables controlling T_c using segmented regression quantiles at maximum response of the dependent variable ($T=0.8$). The evaluation was conducted using weighted T_c for the entire orchard, as well as T_c for the individual monitoring trees. The data from the different seasons of measurements were combined, since similar patterns of environmental control of T_c were observed across the different seasons. The point at which T_c is limited in relation to increased ET_o was identified.

4.3 RESULTS AND DISCUSSION

4.3.1 Aerodynamic and canopy conductances, and resultant decoupling coefficient

Daily variations in aerodynamic and bulk canopy conductances, and the resultant coupling of T_c to the atmosphere (represented by the decoupling coefficient – the Ω factor) throughout the growing season were compared between pecans and macadamias in order to explain the mechanism of crop water use in response to atmospheric conditions (Figure 4.1).

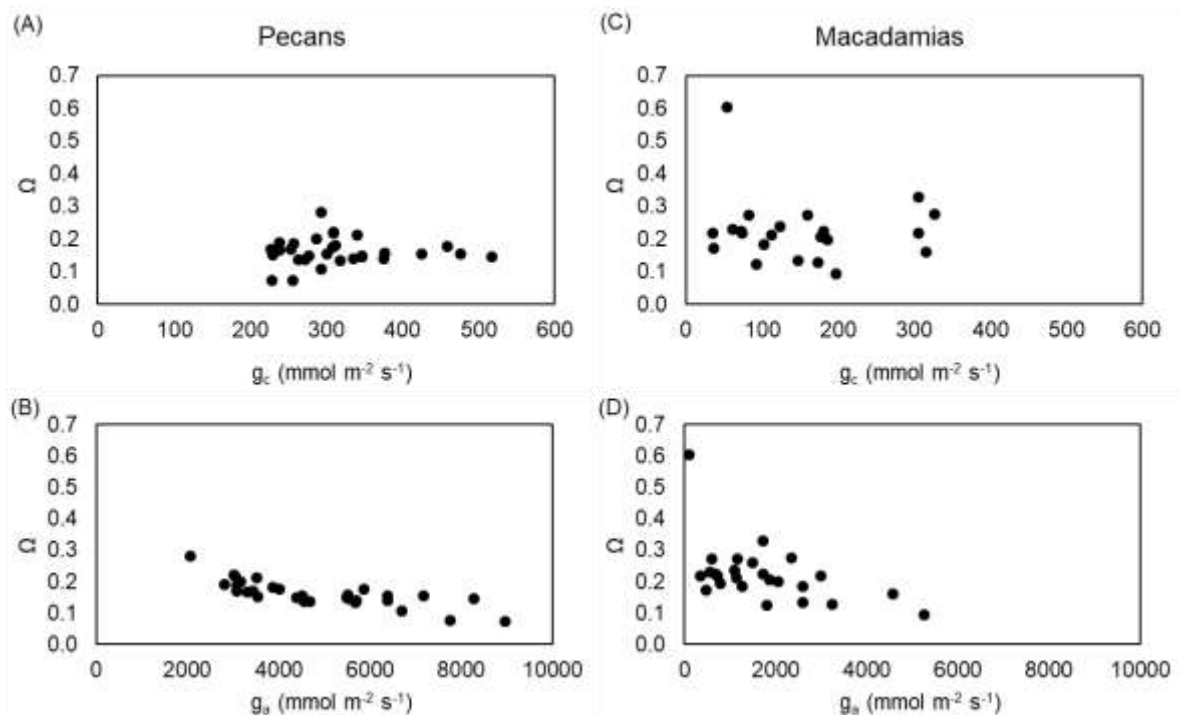


Figure 4.1 Relationships between daily estimates of the (A, C) decoupling coefficient (Ω) and canopy conductance (g_c) and the (B, D) decoupling coefficient and aerodynamic conductance (g_a) for pecans and macadamias, respectively. Data shown correspond to 32 days of measurements in the pecan orchard and 23 days of measurements in the macadamia orchard.

Considerable variations in day-to day g_c were observed for pecans and macadamias. Daily estimates of g_c for pecans ranged from 227 to 518 mmol m⁻² s⁻¹, and averaged 313 mmol m⁻² s⁻¹ across the period of measurements in February 2012 (Figure 4.1A). Macadamias, on the other hand, had much lower g_c (varying between 37 and 326 mmol m⁻² s⁻¹, with an average of 157 mmol m⁻² s⁻¹ throughout the season, Figure 4.1C). Similar contrasting magnitudes of g_c have been observed between other deciduous (apple, walnut, peach and pistachio – range 240 to 365 mmol m⁻² s⁻¹) and evergreen species (olive and orange – range 74 to 100 mmol m⁻² s⁻¹) (Villalobos *et al.* 2013). Low g_c in macadamias suggests the presence of a water conservation strategy in these trees, which may contribute to reduced crop water use throughout the growing season. Higher g_c values in pecan trees might be associated with a greater ability of roots to take up water, bigger trunk diameters and therefore larger sapwood areas (1025 cm² for pecans as compared to 101 cm² for macadamias) and perhaps higher hydraulic

conductance, which may contribute to higher T_c rates for pecans as compared to macadamias.

Values of Ω were generally low for pecans (varying between 0.08 and 0.28) and macadamias (ranging between 0.1 and 0.6), which demonstrates a strong influence of VPD on T_c . In other words, T_c was conditioned by aerodynamic conditions rather than radiation conditions in both tree nut crops (Figure 4.1). This would imply that in both trees a fractional change in stomatal conductance would lead to an equal fractional change in T_c . Canopy transpiration of pecan trees was on average more coupled to the atmosphere (average $\Omega = 0.16$) than macadamia trees (average $\Omega = 0.22$).

Aerodynamic conductance was generally higher in the pecan orchard (between 2060 and 8969 $\text{mmol m}^{-2} \text{s}^{-1}$, with an average of 4854 $\text{mmol m}^{-2} \text{s}^{-1}$), as compared to the macadamia orchard (between 97 and 5270 $\text{mmol m}^{-2} \text{s}^{-1}$, with an average of 1749 $\text{mmol m}^{-2} \text{s}^{-1}$). This was likely attributable to pecan trees being taller than macadamia trees (~15 m, as compared to 6 m macadamia trees), which resulted in more vigorous air mixing and greater crop roughness, causing a reduction in the Ω factor (Jarvis, 1986). Despite their differences in height, both crops showed low Ω values, which suggests that in conditions of high available energy, wind speed and VPD, which are normally found when ET_o is relatively high, it may be expected that tall horticultural species with high inner resistances to water flow do not respond directly to the atmospheric water demand (Marin and Angelocci, 2011). The strong T_c coupling to the atmosphere in these crop species contribute to limited T_c rates under conditions of increased atmospheric evaporative demand. This study provides the first insight into the aerodynamic and canopy conductances of pecan and macadamia orchards, and the impact of their relationship in the coupling of T_c to the atmosphere for these tree nut species. Such findings will assist in defining the environmental control of their T_c and therefore the selection an appropriate modelling approach to estimate T of these crops more accurately.

4.3.2 Daily variations of canopy transpiration in response to daily changes in the atmospheric environment

Maximum T_c of pecan trees during the 2010/2011 season varied from 2.7 mm day⁻¹ at the beginning and end of the season when canopy cover was at a minimum to 6.1 mm day⁻¹ during the mid-season when canopy cover was at a maximum (Figure 4.2A, B, C, D, E). Throughout the season, daily average T_c for pecans was 3.9 mm day⁻¹, whilst total seasonal T_c was 971 mm. Values of orchard T_c for macadamia trees during the 2011/2012 season varied from 2.0 mm day⁻¹ in June when canopy cover and atmospheric evaporative demand (ET_o) were the lowest to 4.0 mm day⁻¹ in October when ET_o was highest (Figure 4.2F, G, H, I, J). Throughout the season, daily average T_c for macadamias was 2.4 mm day⁻¹, whilst total seasonal T_c was 862 mm.

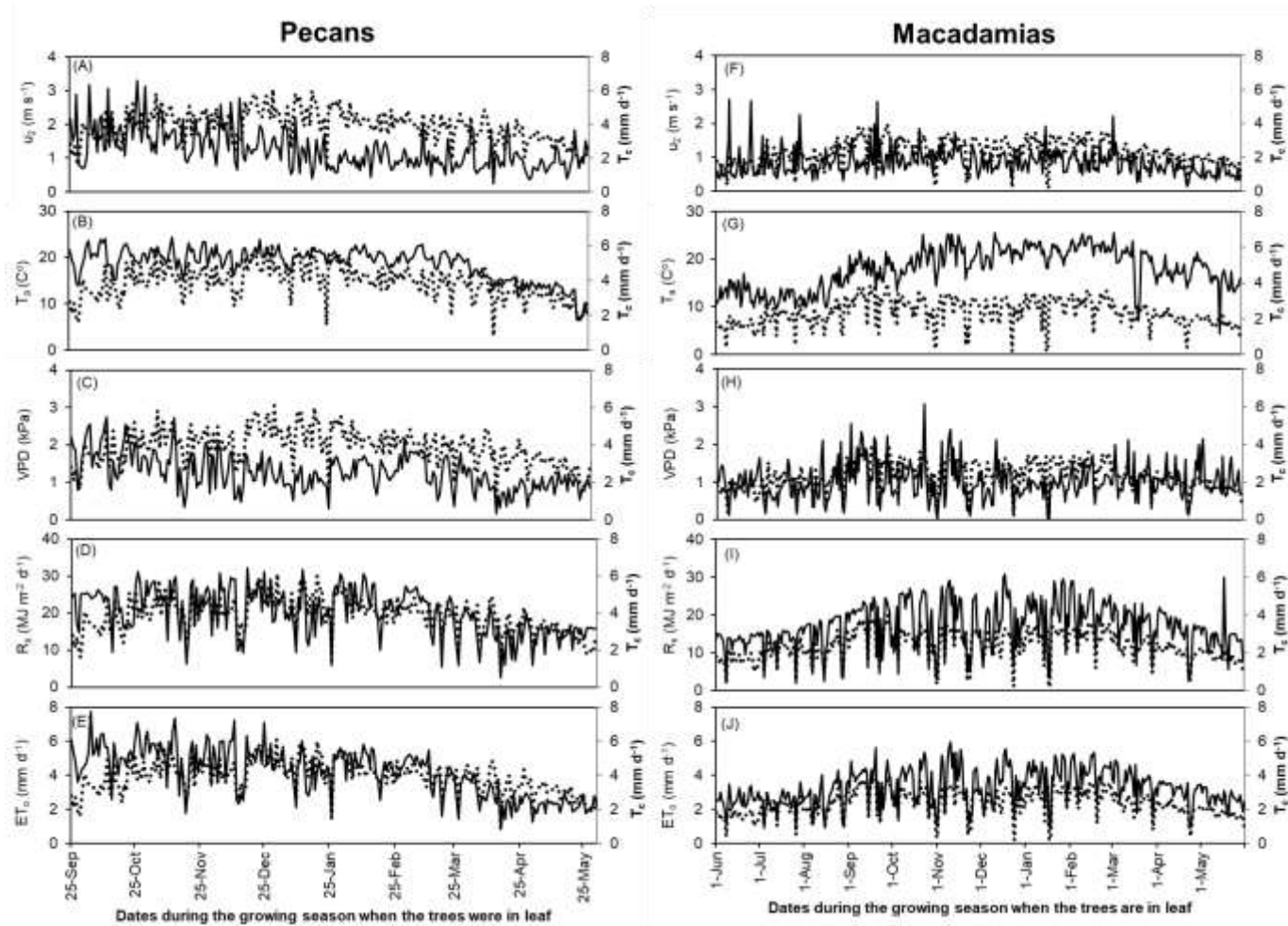


Figure 4.2 Daily variations in canopy transpiration - T_c (dotted line) in response to daily changes in (A, F) wind speed – u_2 , (B, G) air temperature - T_a (C, H) vapour pressure deficit - VPD, (D, I) solar radiation - R_s and (E, J) atmospheric evaporative demand - ET_o (solid lines) for pecans during the 2010/2011 growing season and macadamias during the 2011/2012 growing season.

As illustrated in Figure 4.2, T_c was generally higher for pecans in comparison to that of macadamias, regardless of the atmospheric demand (total ET_o during the growing season of pecans was 1036 mm, whereas during the growing season of macadamias it was 1196 mm). Canopy transpiration of macadamias remained fairly constant throughout the season despite the increase in mean air temperature (T_a) (Figure 4.2G), solar radiation (R_s) (Figure 4.2I) and ET_o (Figure 4.2J) in spring (September to November) and summer (December to February). It is evident that macadamia trees exhibited a more conservative water use strategy, as compared to pecans, by maintaining relatively constant T_c rates under increased ET_o (Figure 4.2). A contrasting water use pattern is further illustrated in Figure 4.3, through a comparison between their transpiration crop coefficients (K_t , which is the ratio between T and ET_o). Values of K_t of macadamias tended to decrease throughout the growing season, while K_t values for pecans showed an opposite trend. This indicates that T_c of macadamias does not linearly follow ET_o , as opposed to the general trend observed for pecans. Results presented in Figures 4.2 and 4.3 only demonstrate how the crop generally responds to atmospheric variability over a growing season, but they do not provide an insight on the full distribution of possible changes in T_c at every level of an atmospheric variable. In other words, what influence will relatively low and high levels of each individual atmospheric variable have on the variability of T_c ? The answers to this question are presented in the next section using a segmented quantile regression analyses to study the variability of T_c in response to changes in every level of an individual atmospheric variable.

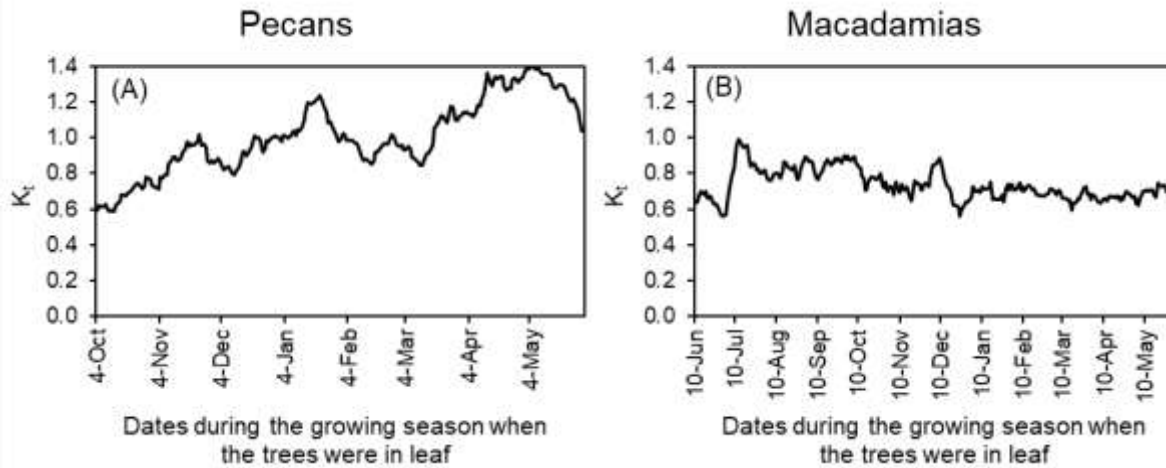


Figure 4.3 Changes in transpiration crop coefficients (K_t) for (A) pecans throughout the 2010/2011 growing season and (B) macadamias throughout the 2011/2012 growing season, for the period when the trees were in leaf.

4.3.3 The response of canopy transpiration to the individual effects of different environmental variables

The individual effect of volumetric soil water content (θ) on the different portions of the distribution of T_c , was evaluated using segmented quantile regression analysis (Figure 4.4). Canopy transpiration of macadamias did not respond positively under the range of θ at the experimental site (0.20 to 0.26 m m^{-3}) (Figure 4.4B), unlike pecans in which T_c increased with higher levels of θ (up to 0.32 m m^{-3}), above which T_c declined (Figure 4.4A). The poor response of T_c of macadamia trees with increasing θ suggests that these trees are very sensitive to waterlogged conditions and do not necessarily benefit from irrigation applied over and above the annual rainfall of between 840 and 890 mm . This is perhaps not unexpected as Trochoulias and Johns (1992) observed negligible differences in tree performance between irrigated and non-irrigated treatments when macadamia tree growth and yield was observed under field conditions in a high rainfall area ($> 1200 \text{ mm}$) of subtropical Australia. Although this response was observed under higher rainfall conditions, it may not contradict the results from this study, as the orchard in this study was drip irrigated, which increases plant available soil water, as compared to sprinkler irrigation used in the study by Trochoulias and Johns (1992). Unfortunately, there were no measurements of θ reported in the study by Trochoulias

and Johns (1992) which makes it difficult to assess how soil water conditions restrict growth and yield of macadamias. As a result, the value of irrigation in macadamias to optimise T remains unclear. Even though the results from this study have shown no response of T_c of macadamias to increased θ , the range of θ studied was quite limited (0.20 to 0.26 $\text{m}^3 \text{m}^{-3}$), as the soil profile was often kept close to field capacity throughout the experimental period, which restricted the number of observations under drier conditions. The lack of clear evidence indicating a requirement for irrigation in macadamia trees is, however, not surprising, as these trees have an extensive and spreading root system that aids in extraction of water from deep soil layers ($> 1.2 \text{ m}$) (Stephenson *et al.* 2003). The leaves also have xeromorphic features, with stomata only found on the abaxial surface of the leaf, which contribute to regulated water loss (Stephenson and Gallagher, 1989; Stephenson and Trochoulias, 1994; Carr, 2012a).

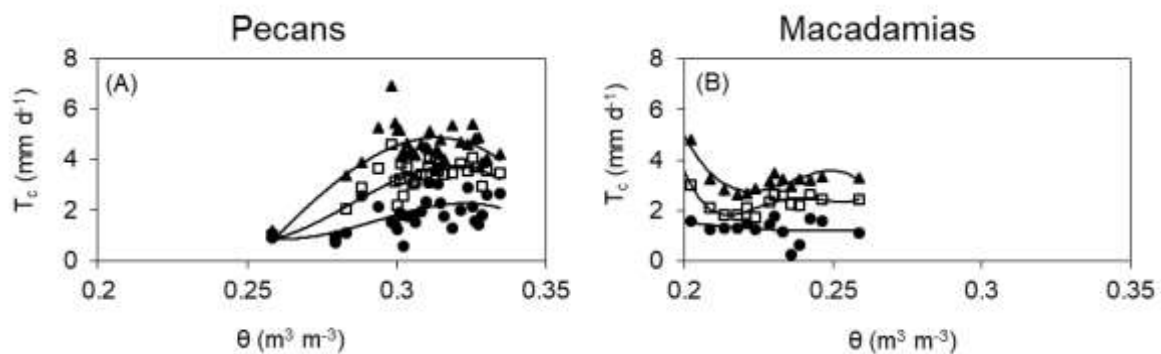


Figure 4.4 Canopy transpiration (T_c) as influenced by daily changes in volumetric soil water content (θ) for (A) pecan and (B) macadamia trees. Only selected regression quantiles of the distribution of daily canopy transpiration were plotted, namely 0.1 (black circles), 0.5 (open squares) and 0.9 (black triangles).

The individual effects of the different daily atmospheric variables (u_2 , T_a , VPD and R_s) on the different portions of the distribution of T_c were also evaluated using segmented quantile regression analysis for pecan and macadamia trees, in order to assess whether there is a limitation on T_c of these tree species under specific atmospheric conditions (Figure 4.5).

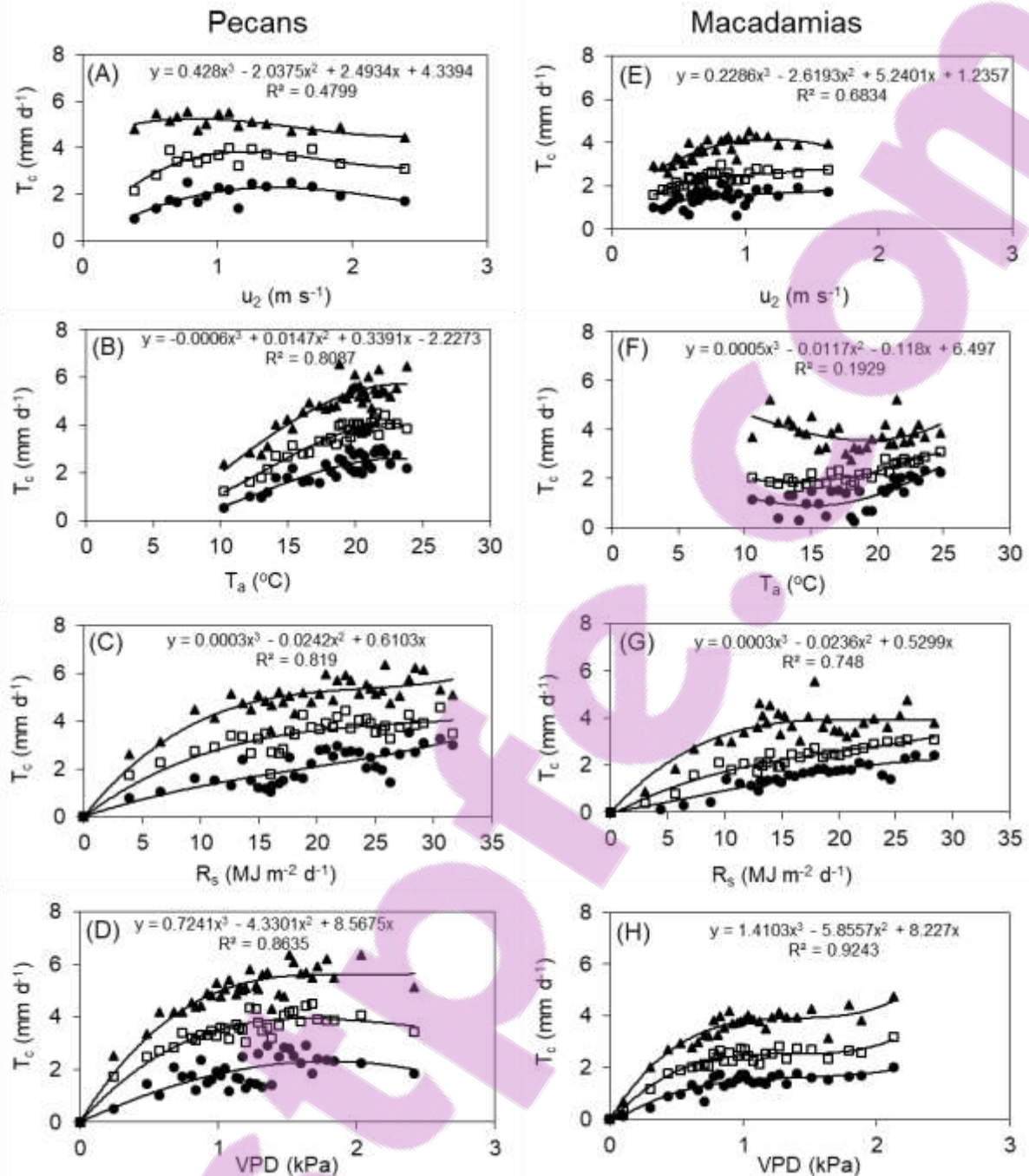


Figure 4.5 Canopy transpiration - T_c as influenced by daily changes in (A, E) wind speed – u_2 , (B, F) mean air temperature - T_a , (C, G) vapour pressure deficit - VPD and (D, H) solar radiation - R_s for pecan and macadamia trees. Only selected regression quantiles of the distribution of daily canopy transpiration were plotted, namely 0.1 (black circles), 0.5 (open squares) and 0.9 (black triangles). The regression equation represents the 0.9 quantile.

As observed in Figure 4.5, the response of T_c to changes in the different environmental variables followed a third degree polynomial relationship in the majority of its distribution. Canopy transpiration of pecans declined at $u_2 > 0.8 \text{ m s}^{-1}$ at all the different quantiles of its distribution, whereas macadamia trees were able to maintain T_c under a wider range of u_2 (up to $u_2 < 1.3 \text{ m s}^{-1}$) (4.5A and E). Wind speed is directly related to boundary layer conductance, and as a result, an increase in u_2 would lead to an increase in the boundary layer conductance, causing reduced resistance to water vapour diffusion and heat transfer between the leaf and its surroundings. This would lead to a small difference between leaf temperature (due to the cooling of the leaf) and air temperature, thus reducing the gradient driving water loss through the stomata (Martin *et al.* 1998; Schymanski and Or, 2015; Schymanski and Or, 2016). As boundary layer and stomatal conductances operate in series to control T_c , when the former is greater than the latter, stomata become the dominant regulator of water loss, which explains why at u_2 beyond 0.8 m s^{-1} for pecans and 1.3 m s^{-1} for macadamias there was practically no increase in T_c due to the occurrence of stomatal closure. As boundary layer conductance is partly controlled by leaf size (Schuepp, 1993), boundary layer conductance is expected to be greater for pecan trees than for macadamia trees, as pecan trees have smaller leaves. This could have led to earlier stomatal closure in the former species at higher wind speeds ($u_2 > 0.8 \text{ m s}^{-1}$).

Crop response to increased T_a was considerably different between pecans and macadamias, with the pecans showing a general increase in T_c over a greater range of T_a , whilst macadamia T_c only showed a positive response at $T_a > 18 \text{ }^\circ\text{C}$ (Figure 4.5B and F). Decreased response of T_c in macadamia trees at T_a below $18 \text{ }^\circ\text{C}$ might have been associated with a number of reasons: (1) changes in sap viscosity and osmolarity at lower temperatures, as observed in walnuts at $T_a < 15 \text{ }^\circ\text{C}$ (Améglio *et al.* 2004) and olives at $T_a < 13 \text{ }^\circ\text{C}$ (Rousseaux *et al.* 2009); (2) variations in bulk canopy conductance independent from the effect of meteorological variables on the stomatal response (Testi *et al.* 2006) and (3) increased root hydraulic resistance with low soil temperatures in the winter, which result in limited tree water uptake and sap flow through the xylem to the leaves (Pavel and Fereres, 1998).

Canopy transpiration of pecans and macadamias responded more positively to increased levels of R_s at the lower regression quantiles (0.1 and 0.5), whereas at the

upper quantile (0.9) restrictions in the increase of T_c were observed for pecans at $R_s > 21 \text{ MJ m}^{-2} \text{ day}^{-1}$ and macadamias at $R_s > 16 \text{ MJ m}^{-2} \text{ day}^{-1}$, which was particularly evident for the latter species (Figure 4.5C and G). Restrictions in the increase of T_c of macadamias at lower R_s levels might be associated with the influence of increased levels of other atmospheric variable, such as VPD, on the response of T_c , which is likely to occur in the upper quantile of its distribution.

Both pecans and macadamias exhibited characteristics suggesting strong stomatal control over T_c in all the different portions of its distribution when VPD was above 1.4 kPa for pecans and above 1.2 kPa for macadamias. This suggests that the response of T_c to increasing VPD reaches a plateau where stomatal closure beyond a threshold VPD restricts further increase in T_c (Figure 4.5D and H). This was particularly evident for pecans in which the curve of T_c vs VPD remained flat or even decreased slightly after the threshold of 1.4 kPa had been reached, while the increase in T_c of macadamias considerably slowed down but did not completely stabilize after the threshold of 1.2 kPa. This supports the higher decoupling factor found in pecans ($\Omega = 0.16$) compared to macadamias ($\Omega = 0.22$). Whilst Lloyd (1991) reported a higher VPD threshold value for macadamias of 1.5 kPa, based on a relationship between stomatal conductance and transpiration of selected leaves, a comparison between Lloyd (1991) and this study is not entirely fair. Whole-tree canopy transpiration was used in the current study, where a large variation in stomatal conductance is expected to occur, thus influencing the magnitudes of g_c and T_c . Lloyd (1991), however, used data from individual leaves and measurements were made over protracted periods in a gas exchange cuvette clamped onto the selected leaves. As a result, his study might not reflect field conditions.

Of all the different individual atmospheric variables selected for analyses in this study (u_2 , T_a , VPD and R_s), VPD, followed by R_s , were the variables that best explained the daily variability in T_c for both pecans (R^2 between 0.82 - Figure 4.5C and 0.86, - Figure 4.5D) and macadamias (R^2 between 0.75 -Figure 4.5G and 0.92 -Figure 4.5H). These results suggest that a canopy conductance model should be considered for modelling daily transpiration of pecans and macadamias, which uses VPD and R_s as the driving atmospheric variables. The response of T_c to increasing VPD had equal effects in all the different portions of the distribution of T_c studied for pecans and macadamias, once

again suggesting that VPD is the most dominant atmospheric variable controlling T_c of these tree nut crops, which confirms the findings of Lloyd (1991) for the regulation of T_c in macadamia trees.

Whilst there is some evidence of VPD driving T_c of macadamias, there are no studies showing similar relations for pecans or modelling of pecan water use using a canopy conductance approach. Pecan water use has most often been modelled using a crop coefficient approach which has given good estimations of evapotranspiration (ET) on a seasonal and monthly basis (Miyamoto, 1983; Sammis *et al.* 2004; Wang *et al.* 2007; Samani *et al.* 2009; Samani *et al.* 2011). The fact that soil evaporation forms a considerable proportion of crop ET in discontinuous canopies could possibly explain the good performance of crop coefficient models for estimation of ET of pecans, as ET is closely related to ET_o . In addition, most of these models were developed for monthly estimates of pecan ET, and as a result, accuracy on a shorter time scale, e.g. daily, would in all likelihood be reduced. It is therefore important to investigate the performance of a canopy conductance model for estimation of daily T of pecans as well. Preference should be given to a canopy conductance model which includes VPD and R_s as the main drivers for T . However, the exclusion of certain atmospheric variables such as T_a which was found to be the third variable most positively correlated to T_c for pecans ($R^2 = 0.81$, Figure 4.5B) and u_2 for macadamias ($R^2 = 0.68$, Figure 4.5E), might, to certain extent, reduce the accuracy of model predictions, since these factors might also play certain roles in controlling g_c and T_c of these tree nut crops.

Results from this study suggest that the closure of stomata to minimize T_c losses in both pecans and macadamias is likely to be primarily triggered by relatively high levels of VPD or R_s (Figure 4.5), which is most probably aggravated by a combination of the two. Studies on annual cereal and oil seed crops have reported changes in the response of T_c to increased VPD due to interactions with other atmospheric variables such as T_a (Yang *et al.* 2012; Seversike *et al.* 2013). This suggests that the control of T_c of pecans and macadamias in response to atmospheric variability should be examined further, by evaluating interactions between the most important controlling factors of T_c , and their impact on the response of T_c to an increase in the atmospheric demand.

4.3.4 The response of canopy transpiration to an increase in atmospheric evaporative demand under various atmospheric conditions

Changes in T_c of pecans and macadamias in response to increased ET_o were further investigated by examining the integrated effect of the various atmospheric variables on T_c (Figure 4.6A and F). Interactions between previously identified relatively low and high levels for the most controlling atmospheric variables of T_c (VPD and R_s , Figure 4.4C, D, G, H) were selected for analysis in Figure 4.6B, C, D, E for pecans and Figure 4.6G, H, I, J for macadamias.

The response of T_c to fluctuations in ET_o was slightly different between pecans (Figure 4.6A) and macadamias (Figure 4.6F), when examining the whole range of prevailing atmospheric conditions at the study sites, which was particularly evident at low levels of VPD and R_s (Figure 4.6B and G). Canopy transpiration of pecans rapidly increased (from 2.3 up to 5.4 mm day⁻¹) at ET_o below 4 mm day⁻¹, and remained fairly constant at ET_o above 4 mm day⁻¹, indicating a fairly conservative water use strategy during these periods of relatively high ET_o . In contrast to pecans, T_c of macadamias showed a gradual increase (from 1.8 to 3.6 mm day⁻¹) almost throughout the whole range of ET_o studied, with T_c only remaining constant or declining slightly at ET_o above 5 mm day⁻¹, suggesting a conservative water use strategy throughout the entire season or within the whole range of prevailing ET_o at the study period. This advocates that pecans and macadamias present slightly different mechanisms of gas exchange. At low ET_o pecans will open stomata to sustain high gas exchange but then will start to throttle water use, which is in contrast to macadamias that have much lower T_c rates at low ET_o indicating perhaps higher resistance to gas exchange within the leaf. Sperry (2000) emphasizes that such water use is typical of drought-adapted species, which generally leads to a more gradual use of soil water even under non-limited water supply conditions. This typically makes these species less susceptible to cavitation.

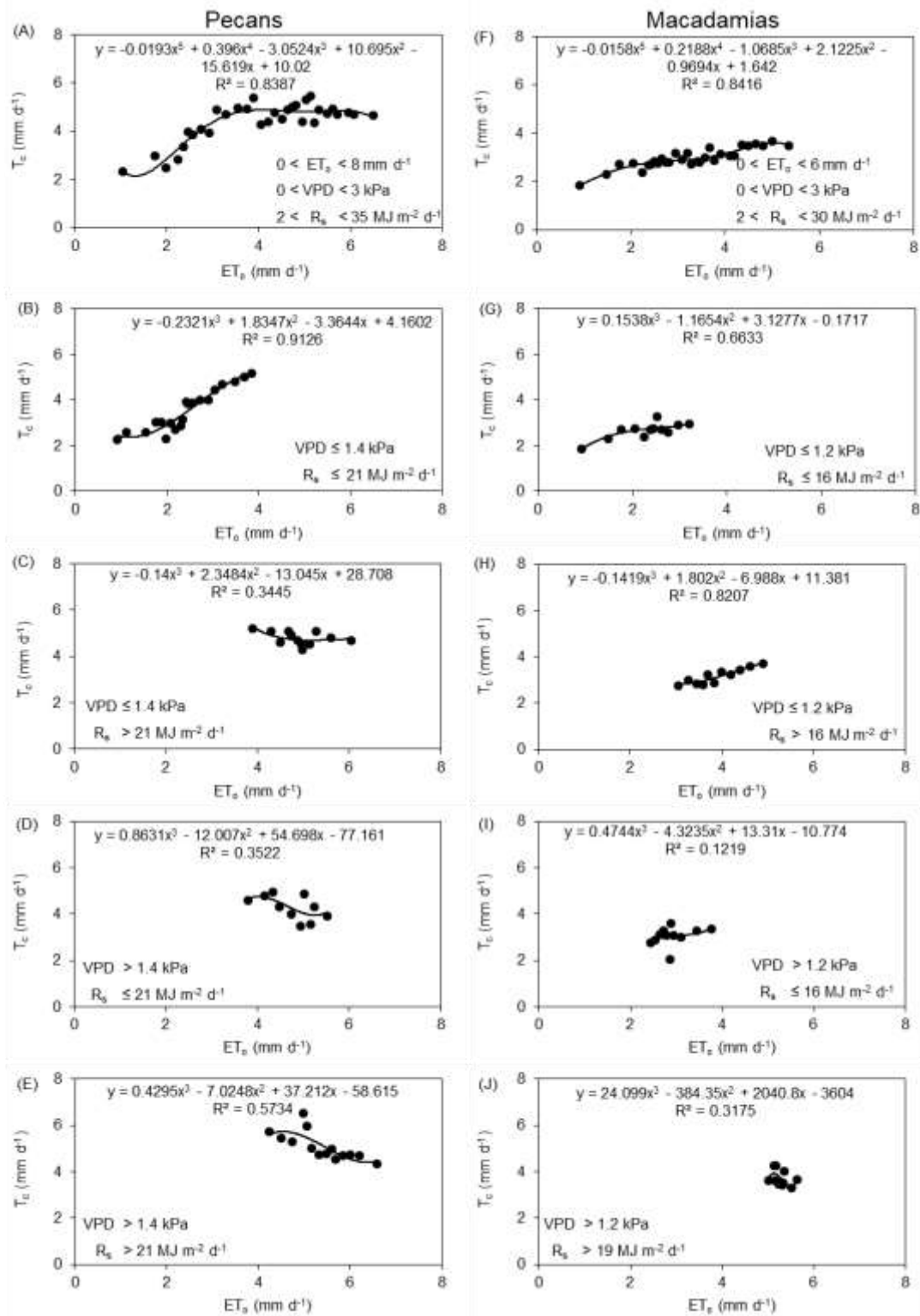


Figure 4.6 Average response of canopy transpiration (T_c) at the most extreme regression quantile to daily changes in atmospheric evaporative demand (ET_a) at (A, F) the whole range of prevailing conditions, (B, G) low levels of VPD and R_s , (C, H) low VPD and high R_s , (D, I) high VPD and low R_s , (E, J) high VPD and high R_s for pecans and macadamias, respectively. The equation and R^2 for the best curve fit are provided for each set of conditions.

Further increases of T_c of pecans beyond 5.4 mm day^{-1} were limited by either high R_s ($> 21 \text{ MJ m}^{-2} \text{ day}^{-1}$, Figure 4.6C) or high VPD ($> 1.4 \text{ kPa}$, Figure 4.6D) and was more aggravated by the combination of high levels of R_s and high VPD (Figure 4.6E). Canopy transpiration of macadamias, on the other hand, showed no limitations at high R_s ($> 16 \text{ MJ m}^{-2} \text{ day}^{-1}$, Figure 4.6H) and demonstrated a more gradual increase of T_c at VPD $> 1.2 \text{ kPa}$ (Figure 4.6I), with noticeable reductions of T_c only observed under conditions of high VPD ($> 1.2 \text{ kPa}$) combined with high levels of $R_s > 19 \text{ MJ m}^{-2} \text{ day}^{-1}$ (Figure 4.6J). Indeed, the effect of VPD on T_c of both pecans and macadamias changed when interactions between VPD and R_s were considered, as observed in cereals and oil seed crops, when VPD and temperature interactions were evaluated in relation to T_c (Yang *et al.* 2012; Seversike *et al.* 2013). A combination of high VPD and high R_s restricted the increase of T_c even more in both pecans and macadamias, as compared to high levels of either of the factors alone. Thus, studying the effect of VPD alone on T_c of fruit tree species, as reported previously (Higgins *et al.* 1992; Rousseaux *et al.* 2009; Marin and Angelocci, 2011), may provide limited or misleading information on the regulation of T_c . There is only one study conducted by Lloyd (1991) which assessed the response of transpiration of macadamias to increased VPD, under various conditions of T_a at low and high light intensities, in which transpiration remained relatively constant across the range of VPD studied, at both low and high light intensity levels. However, as mentioned above, this study was conducted under controlled environmental conditions for a relatively short period of time (10 days) on a small number of leaves, which may not be representative enough to make valid inferences about responses under field conditions. In another study, Lloyd *et al.* (1991) determined the response of stomatal conductance (g_s) of field-grown macadamias to increased photon irradiance at low (0.5 kPa), medium (2.0 kPa) and high (3.0 kPa) VPD. These authors found considerable reductions in the magnitudes and rates of g_s at high, followed by medium VPD. The disadvantage of their study was that they could only analyze the variability of g_s to specific levels of VPD, which does not allow one to identify the exact threshold at which the dependent variable is limited. This was made possible in this study using a quantile regression approach, by examining the full distribution of possible changes in the dependent variable at every level of the most important controlling atmospheric variable. Even though pecans and macadamias presented slightly different mechanisms of transpirational responses in relation to changing atmospheric conditions, a point was evident in both crops ($R_s > 21 \text{ MJ m}^{-2}$

day⁻¹ or VPD > 1.4 kPa for pecans, Figure 4.6C and D; a combination of $R_s > 19 \text{ MJ m}^{-2} \text{ day}^{-1}$ and VPD > 1.2 kPa for macadamias, Figure 4.6J), above which there was no further increase in T_c . This suggests the presence of a water-saving strategy regulated through stomatal closure in these crops, as seen in other perennial tree crops (Lloyd, 1991; Lloyd *et al.* 1991; Wullschleger *et al.* 2000). These results are in agreement with the high degree of coupling found for both pecan and macadamia trees, as presented in Section 4.3.1.

4.3.5 Manipulation of water loss by pecan and macadamia trees under non-limited soil water conditions

The environmental dependency of T_c in pecan and macadamia trees, presented in Figures 4.4 and 4.6 helps to explain the mechanism of water use in these two tree nut species. Pecan trees were able to transpire at higher rates with increased θ (Figure 4.4A), while T_c of macadamia trees remained fairly unresponsive to increased θ (Figure 4.4B), which is probably a reflection of higher canopy conductances of pecan trees as compared to macadamia trees. Differences in the magnitudes of their T_c rates were particularly evident under relatively low levels of ET_o ($ET_o < 4 - 5 \text{ mm day}^{-1}$), as evident in Figure 4.6A and B for pecans and Figure 4.6F and G for macadamias. On the other hand, under conditions of relatively high levels of ET_o ($\geq 4 - 5 \text{ mm day}^{-1}$), the atmospheric demand was likely to exceed the rate of water supply to the leaves in both pecan and macadamia trees, causing stomatal closure to prevent possible cavitation or embolism forming in the xylem as a result of low leaf water potentials. This was particularly evident at relatively high levels of VPD and/or R_s for pecans (VPD > 1.4 kPa and/ or $R_s > 21 \text{ MJ m}^{-2} \text{ day}^{-1}$; Figure 4.6C, D and E) and macadamias (VPD > 1.2 kPa and/ or $R_s > 16 \text{ MJ m}^{-2} \text{ day}^{-1}$; Figure 4.6I and J).

Whilst the pattern of root water uptake of macadamia trees remained fairly constant throughout the growing season, even under relatively low levels of VPD and R_s , suggesting that these trees were limited by water supply provided by the root system to the leaves throughout the entire study period, pecan trees were possibly demand-limited under relatively low levels of VPD and R_s . Pecan trees showed increased root water uptake and T_c rates during these periods, and only became supply-limited at relatively high levels of VPD and R_s , when a reduction in T_c rates with increased θ was observed. The water supply limitation from the roots to the leaves of macadamias

causes a mismatching between rates of delivery to the leaves and rates demanded by the atmosphere, particularly under conditions of high atmospheric evaporative demand. As a result, the stomata closes to prevent leaf water potentials from dropping too low, and in order to balance water uptake and loss (Campbell and Turner, 1989). The fairly constant T_c rates of macadamia trees throughout the growing season is probably attributable to a natural surviving mechanism these trees have in order to cope with drought. Although macadamias are reported to have an effective root system for extracting water (Lloyd *et al.* 1991), they are likely to have increased resistances in their leaves to both CO_2 and water diffusion through the leaf, due to their thick xeromorphic leaves with sclerified bundle sheath tissue and stomata found only on the abaxial surface of the leaf (Carr, 2012a). Nevertheless, the presence of a water supply limitation to the leaves of macadamias should be supported by additional measurements of hydraulic conductance/or resistance and water potentials at the stem and leaf levels. If macadamias are indeed isohydric species as suggested in this study, their hydraulic conductivity will be positively dependent on transpiration, which would be responsible for limiting the driving gradient for water flow across the leaves, by minimizing the difference in stem-leaf water potentials.

4.4 CONCLUSIONS

Transpiration of irrigated pecan and macadamia orchards was well-coupled to the atmosphere (with typical Ω varying between an average of 0.16 and 0.22). Pecans had lower Ω values (0.08 - 0.28) and higher canopy conductances (g_c) (227 to 518 $\text{mmol m}^{-2} \text{s}^{-1}$) compared to macadamias ($\Omega = 0.1 - 0.6$ and $g_c = 37$ and 326 $\text{mmol m}^{-2} \text{s}^{-2}$). The high degree of coupling of transpiration in these fruit tree species influenced the manner in which transpiration responded to the environment. Canopy transpiration in both pecans and macadamias was primarily driven by VPD, with T_c rates of both crops remaining fairly constant once a threshold VPD had been reached (1.4 kPa for pecans and 1.2 kPa for macadamias), thus indicating strong stomatal control of T_c during these periods. The decrease in T_c rates was more pronounced in pecan trees compared to macadamia trees during the experimental period, which is probably the result of stronger transpiration coupling in the former species.

Pecan and macadamia trees showed slightly different mechanisms of crop water use. Pecan trees were able to transpire at faster rates (2.3 to 5.4 mm day⁻¹) with increased volumetric soil water content (being demand-limited during these periods) until an atmospheric threshold had been reached (VPD = 1.4 kPa, R_s = 21 MJ m⁻² day⁻¹ and ET_o = 4 mm day⁻¹), above which T_c remained fairly constant, progressing under supply-limited conditions. Canopy transpiration of macadamia trees, on the other hand, remained fairly irresponsive to increased volumetric soil water content throughout the entire growing season (being supply-limited), showing a slower increase (1.8 to 3.6 mm day⁻¹) with T_c rates progressively decreasing in response to increased ET_o, up to a threshold of VPD = 1.2 kPa, R_s = 19 MJ m⁻² day⁻¹ and ET_o = 5 mm day⁻¹, above which T_c remained fairly constant or even decreased. Slightly contrasting mechanisms of crop water use between pecans and macadamias were further reinforced by the differences in the variability of their transpiration crop coefficients (K_t). Values of K_t of macadamias tended to decrease throughout the growing season, while K_t values for pecans showed an opposite trend. Despite their differences in the pattern of crop water use, both tree species revealed the presence of a water-saving strategy, which was manifested through stomatal regulation. The common presence of a water-saving strategy in both crops is typically associated to strong transpiration coupling to the atmosphere in tall deciduous and evergreen perennial tree crops, while their slightly distinct crop water use patterns are likely related to their varying growth habits. Evergreen species like macadamias tend to be more conservative with respect to water use than deciduous species like pecans, because they need to tolerate severe water stress during the dry winter season, which deciduous species avoid.

Quantile regression analyses provided a more detailed insight into the variability of T_c in response to environmental changes. This would not have been possible by a simple day-to-day comparison between the dependent and the independent variables. The second most important atmospheric variable driving T_c was R_s, following VPD, and in both response curves, changes in T_c showed strong stomatal regulation. This suggests that a canopy conductance model should be considered for modelling daily transpiration of pecans and macadamias, which uses VPD and R_s as the driving atmospheric variables. The use of such modelling approach could contribute to improved irrigation scheduling of these orchard crops.

CHAPTER 5: MODELLING DAILY TRANSPIRATION OF PECANS AND MACADAMIAS UNDER NON-LIMITING SOIL WATER CONDITIONS

5.1 INTRODUCTION

Appropriate irrigation scheduling is crucial to supplement rainfall in order to achieve optimum yield and quality of pecans and macadamias. These crops when subjected to water stress (caused by excessive or shortage of water supply), often show reduced yield, nut mass and vegetative growth (Garrot *et al.* 1993; Carr, 2012a). Accurate irrigation scheduling can be done through the quantification of crop water requirements, defined as the depth or amount of water needed to match water loss through crop evapotranspiration (ET) (Allen *et al.* 1998). Transpiration (T) is usually the biggest component of ET in mature orchards, while soil evaporation (E_s) forms the biggest component of ET in immature orchards (Bonachela *et al.* 1999; Bonachela *et al.* 2001). In either case, accurate quantification of T is important in order to optimize crop productivity through improved irrigation scheduling. By knowing how much water is actually lost through T (which is a direct indicator of canopy performance and crop productivity), great water savings can be made through the use of more efficient irrigation systems, such as subsurface drip irrigation for example (Ayars *et al.* 2015). In addition, precise quantification of T is necessary to assess the validity of ET partitioning approaches and to investigate opportunities for reducing T without compromising crop yield through deficit irrigation strategies (Villalobos *et al.* 2013).

Crop transpiration is highly variable, and as a result, its measurement under all possible combinations of climate and management practices is not feasible, which makes the use of models crucial for its estimation. Transpiration of annual and perennial crops is often estimated separately from E_s using the FAO-56 dual crop coefficient approach, through a computation making use of a basal crop coefficient (K_{cb}) and a soil evaporation coefficient (K_e) (Allen *et al.* 1998; Allen *et al.* 2000; Allen and Pereira, 2009; Allen *et al.* 2005; Er-Raki *et al.* 2010; Rosa *et al.* 2012a; Rosa *et al.* 2012b). This approach is relatively simple and requires fewer input parameters than many other approaches for estimating T, such as the single-layer Penman-Monteith

or multi-layer ET models like that by Shuttleworth and Wallace (Allen *et al.* 2000; Zhao *et al.* 2015). However, predictions of T may be slightly overestimated due to the fact that K_{cb} values include small amounts of E_s occurring by diffusion in the surface layer when the soil is dry (Allen *et al.* 2005; Villalobos *et al.* 2013). Besides, standard crop coefficients for fruit trees are highly variable across different environmental and orchard management conditions, and as a result, models which are based on a crop coefficient approach may not always be transferable (Wang *et al.* 2007; Villalobos *et al.* 2013; Marsal *et al.* 2014). Furthermore, the applicability of the crop coefficient approach may be limited for perennial crops because it assumes demand limited transpiration, while there is evidence of a supply limitation of water to the leaves in such crops, which results in stomatal closure and a reduction in the rate of increase in T relative to atmospheric evaporative demand (Nicolás *et al.* 2008; Rousseaux *et al.* 2009; Marin and Angelocci, 2011; Taylor *et al.* 2015).

In an attempt to overcome the limitations encountered with the FAO-56 dual crop coefficient approach, Villalobos *et al.* (2013) developed a generalized, simple T model for fruit trees, which is based on a canopy conductance approach, in which direct estimates of T are made as a function of vapour pressure deficit (VPD), solar radiation (R_s) and fraction of intercepted photosynthetically active radiation (f_{IPAR}). Several approaches are available to model canopy intercepted radiation, with varying degrees of complexity (Mariscal *et al.* 2000; Annandale *et al.* 2004; Oyarzun *et al.* 2007; Abraha and Savage, 2010). The model developed by Oyarzun *et al.* (2007) is the most functional amongst all of them due to its simplicity and requirements of relatively easy-to-obtain input parameters, since estimates of tree intercepted radiation are based on changes in canopy porosity, instead of leaf area density. The model developed by Oyarzun *et al.* (2007) is applicable to a wide range of orchard configurations, including hedgerow, overhead trained or isolated trees planted in rectangular patterns. The simplified canopy conductance model developed by Villalobos *et al.* (2013) has also been successfully parameterized for a number of temperate fruit tree species, but not for pecans or macadamias. Model validation studies using this approach are still lacking, which may restrict its applicability as a tool to provide accurate estimates of T for improved irrigation management through reduction of E_s and maximization of T.

It was hypothesized that daily T of pecans and macadamias would be more accurately estimated using the canopy conductance approach than using a crop coefficient approach. This is due to the strong stomatal regulation of T in these tree nut species, which causes a reduction in the rate of increase in T relative to the increase in atmospheric evaporative demand. Accurate predictions of f_{IPAR} by pecan and macadamia orchards were expected to improve daily estimates of T considerably, as PAR directly influences canopy conductance regulation. In order to test these hypotheses, this study aimed to parameterize and validate the PAR interception model of Oyarzun *et al.* (2007) and the canopy conductance model developed by Villalobos *et al.* (2013), to estimate daily T of pecans and macadamias, and compare its performance to modelling results obtained with the more widely used FAO-56 dual crop coefficient approach.

5.2 MATERIALS AND METHODS

5.2.1 Field measurements

5.2.1.1 Proportion of shaded ground area and sunflecks within the shaded area

Shaded and sunflecks areas beneath the canopy of two trees in the 7-year-old pecan orchard and 6-year-old macadamia orchard was determined by placing a 6 m x 6 m transparent plastic sheet on the ground surface area allocated to one tree (Figure 5.1), on which the visible shaded or sunfleck area was demarcated with a non-permanent marker. These measurements were conducted at midday. The demarcated shaded or sunfleck area was subsequently placed over a grid with 50 cm² (10 cm x 5 cm) individual sections. The percentage of shade within each square was estimated visually in increments of 10%. Total shade was calculated as the product of the area of all squares and the percent shade within each square as described by Williams and Ayars (2005). The proportion of the shaded area (taken as effective fractional cover - $f_{c\ eff}$) was calculated as the ratio between the total shade and total ground area allocated to each tree. The proportion of sunflecks (an estimation of canopy porosity - a crop-specific parameter that accounts for the radiation that passes unimpeded through gaps within individual tree canopies and reaches the orchard floor, observable as sunlit spots in the cast shaded area on the ground, Oyarzun *et al.* 2007) was

calculated as the ratio between the sunfleck area and the total ground area allocated to each tree. Measurements in the young pecan orchard at Hatfield were conducted every two weeks, while the measurements in the young macadamia orchard at White River every four to eight weeks.



Figure 5.1 Measurement of shaded and sunflecks areas beneath the canopy of 7-year-old pecan trees at the Hatfield experimental site.

5.2.1.2 Hourly measurements of transmitted solar irradiance and its conversion to transmitted photosynthetically active radiation

Delta-T tube solarimeters (Delta-T Devices Ltd, Burwell, Cambridge, England) were installed across the tree row at the different experimental sites to measure hourly global solar radiation transmittance (T_{sg}) through the canopy at different distances from the row (Figure 5.2). The tube solarimeters were set up parallel to the tree row, as suggested by Annandale *et al.* (2004). This was done during one window period in the different pecan study orchards and three window periods in the macadamia study orchard, in order to collect data for validation of a radiation interception model. Data from the tube solarimeters was logged on an hourly basis using a CR10X datalogger (Campbell Scientific, Logan, Utah, USA). All the solarimeters installed in the pecan orchards were re-calibrated against a pyranometer (Campbell Scientific, Logan, Utah, USA) from an automatic weather station installed in close proximity to the experimental

orchards, while those installed in the macadamia orchard were re-calibrated against a Precision Eppley thermopile pyranometer (Campbell Scientific, Logan, Utah, USA).



Figure 5.2 Hourly measurements of global solar radiation penetration through the canopy using Delta-T tube solarimeters positioned at various distances from the 37-year-old pecan tree row (0 m, 2 m and 4.5 m NNE – SSW) at the Cullinan experimental site, between 19 February and 02 March 2012.

Hourly global solar radiation transmittance (T_{Sg}) measured at various positions through the canopy of pecan and macadamia trees was converted to hourly PAR transmittance (T_{PAR}) in order to validate the PAR radiation interception model of Oyarzun *et al.* (2007). This was done using the fixed-ratio of extinction coefficients method, as proposed by Oyarzun *et al.* (2011):

$$\tau_{PAR} = \tau_{Sg}^{\left(\frac{1}{0.7}\right)} \quad (5.1)$$

Converted T_{PAR} values for various positions through the canopy were subsequently used to calculate a weighted average T_{PAR} for the entire canopy.

5.2.2 Crop modelling

5.2.2.1 Modelling of daily fractional photosynthetically active radiation intercepted by the canopy

Daily f_{IPAR} was computed from hourly (h) estimates using the model of Oyarzun *et al.* (2007), in order to estimate daily T of pecan and macadamia orchards. The modelling approach of Oyarzun *et al.* (2007), which assumes that trees are prismatic-shaped porous bodies, is based on the proportion of the orchard floor that is shaded by the trees at any given time, calculated from the geometric relationships of the length of the shadow cast by the trees and the orchard configuration, as illustrated in the diagram 5.3.

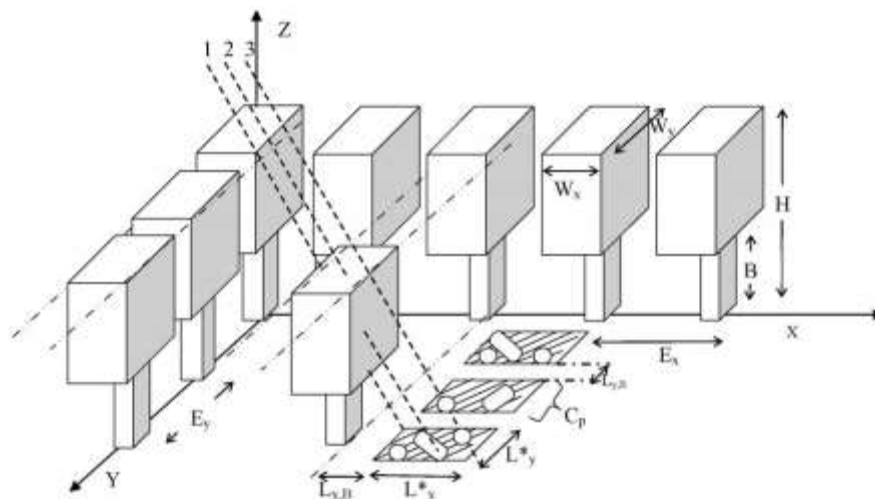


Figure 5.3 Schematic representation of a fruit-tree orchard showing model input variables related to orchard configuration, canopy dimensions, and canopy porosity. Also shown is the interaction between solar rays (---) and the trees when: (1) the beam passes unobstructed below the canopy; (2) the beam passes unobstructed through gaps in the canopy, thus observable as a sunfleck on the shaded ground area (C_p); (3) the beam passes by the edge of the canopy, thus casting a shadow (Oyarzun *et al.* 2007).

The fraction of the orchard floor that is shaded at any given hour ($f_{l,h}$) is calculated as follows (Oyarzun *et al.* 2007):

$$f_{l,h} = \frac{((L_x^* + W_x)W_y + (L_y^* + W_y)W_x) - (W_x W_y)}{E_x E_y} \quad (5.2)$$

where W_x (m) and W_y (m) are the canopy width both perpendicular to the row direction and along the row direction, respectively; E_x (m) is the spacing between rows and E_y (m) is the distance between trees within a row; L_x^* (m) and L_y^* (m) are the effective shadow lengths cast by the trees, both perpendicular to the row and along the row direction, respectively.

$$L_x^* = (L_x - L_{x,B})\sigma \quad (5.3)$$

$$L_y^* = (L_y - L_{y,B})\sigma \quad (5.4)$$

where L_x (m) and L_y (m) are the maximum length of the shadow cast by the trees in the direction perpendicular to the row and along the row, respectively. L_x and L_y is estimated as follows:

$$L_x = H[\tan(\vartheta)\sin(\varnothing_s - \varnothing_R)] \quad (5.5)$$

$$L_y = H[\tan(\vartheta)\sin(\varnothing_s - \varnothing_R)] \quad (5.6)$$

where H (m) is tree height; ϑ (rad) is the zenith angle of the sun calculated using the site location coordinates, solar declination and time of solar noon; \varnothing_s (rad) is the sun azimuth calculated using zenith angle of the sun, solar declination and site location coordinates; \varnothing_R (rad) is the row orientation. Similar equations used to calculate L_x and L_y are used to determine the length of a blank shadow (when radiation reaches the orchard floor practically unobstructed below the tree crown at certain times of the day), perpendicular ($L_{x,B}$, m) and along the row ($L_{y,B}$, m), but using B (height of the lower branches, m) instead of H . The value of σ (a correction factor that accounts for the combined effect of the position of the sun, the slope of the terrain (s), aspect of the slope and \varnothing_s) was calculated as follows:

$$\sigma = \begin{cases} \cos(s), & 45^\circ < (\phi_S - \phi_s) < 135^\circ \\ \frac{1}{\cos(s)}, & 225^\circ < (\phi_S - \phi_s) < 315^\circ \\ 1, & \text{Otherwise} \end{cases} \quad (5.7)$$

Hourly estimates of the shaded fraction of the orchard floor were subsequently used to determine beam radiation interception ($f_{b,h}$), as follows (Oyarzun *et al.* 2007):

$$f_{b,h} = f_{l,h}(1 - C_P^*) \quad (5.8)$$

where C_P^* is an effective canopy porosity, which is obtained from the sunfleck fraction (C_P) on the orchard ground shadowed area and the leaf absorptivity coefficient (α) for PAR, which for fruit trees is assumed equal to 0.85 (Oyarzun *et al.* 2007):

$$C_P^* = \exp[\ln(C_P)\sqrt{\alpha}] \quad (5.9)$$

Regular measurements of C_P using a grid method were not possible in the mature pecan orchard due to the large size of tree canopies, and as a result, C_P was estimated using a thermal time approach as proposed by Lebon *et al.* (2003) for the simulation of canopy development in vineyards:

$$C_P = 1 - \left(\frac{1 - C_{P \min}}{GDD_{\max}} GDD \right) \quad (5.10)$$

$$GDD = \sum_{i=1}^n [0.5(T_{a \max,i} + T_{a \min,i}) - T_b] \quad (5.11)$$

where $C_{P \min}$ is the minimum proportion of foliage gaps attainable throughout the growing season, which was estimated under conditions of maximum canopy cover, taken as $1 - f_{IPAR}$ (fractional interception of photosynthetically active radiation) measured using a ceptometer as described in Section 3.2.1. Growing Degree Days (GDD) is the cumulative thermal time expressed in degree days, calculated using maximum and minimum daily air temperatures ($T_{a \max}$ and $T_{a \min}$) and a base temperature for pecans (T_b) of 15.5 °C (Miyamoto, 1983). GDD_{\max} is the cumulative thermal time until $C_{P \min}$ is reached (453 to 456 degree days, approximately at the end of December). Equation 5.10 was developed to simulate canopy development of

evergreen vineyards, in which C_P decreases throughout the growing season up to a minimum value, which is assumed to stay constant thereafter (Lebon *et al.* 2003). Such a trend does not occur in pecan trees because they are deciduous and the canopy senesces towards the end of the season, which then increases the value of C_P up to a maximum when the trees are completely leafless.

As a result, there was a need to improve Equation 5.10 to simulate the increase in C_P during leaf drop in deciduous pecans trees. This was achieved by predicting the increase in C_P during leaf drop using cumulative thermal time for this period ($GDD_{min,i}$), calculated as a function of minimum air temperatures, following a similar approach employed by Miyamoto (1983) to estimate crop coefficients of pecans during the leaf drop stage. By incorporating such modifications, the expanded version of Equation 5.10 is expressed as follows:

$$C_{P \text{ leaf drop}} = \frac{C_{P \text{ max}} - C_{P \text{ min}}}{GDD_{min,n}} (GDD_{min,i} - 1) + C_{P \text{ min}} \quad (5.12)$$

$$GDD_{min,i} = \sum_{i=1}^n (T_a - T_{a \text{ min},i}) \quad (5.13)$$

where T_a is the long-term average air temperature during the period of $C_{P \text{ min}}$, $T_{a \text{ min},i}$ is the daily minimum air temperature during the period of leaf drop and $C_{P \text{ max}}$ is the maximum C_P when the trees are completely leafless estimated similarly to $C_{P \text{ min}}$.

Hourly estimates of $f_{b,h}$ are used to calculate an orchard-based beam transmittance for each hour ($T_{b,h}$), as (Oyarzun *et al.* 2007):

$$\tau_{b,h} = 1 - f_{b,h} \quad (5.14)$$

A daily averaged effective orchard diffuse transmittance ($T_{d,D}$), from the time of solar sunrise (t_{sr} , 7:00 am) to the time of solar sunset (t_{ss} , 6:00 pm), is obtained following the expression below (Oyarzun *et al.* 2007):

$$\tau_{d,D} = 2 \sum_{h=t_{sr}+1}^{h=t_{ss}} \tau_{b,h} \cos(\theta_h) \sin(\theta_h) \theta_{h-(h-1)} \quad (5.15)$$

Then, the diffuse radiation interception fraction for the orchard ($f_{d,D}$) is obtained as:

$$f_{d,D} = 1 - \tau_{d,D} \quad (5.16)$$

Thus, hourly values of fractional PAR interception ($f_{IPAR,h}$) are obtained as (Nouvellon *et al.* 2000):

$$f_{IPAR,h} = f_{b,h}F_{PARb,h} + f_{d,D}F_{PARd,h} \quad (5.17)$$

where $F_{PARb,h}$ and $F_{PARd,h}$ are the beam and diffuse PAR fractions, respectively. These terms are calculated using the zenith angle of the sun, a correction factor that accounts for topographic effects on incident beam radiation, site location coordinates, solar declination and daily incident global solar irradiance, following the procedure outlined by Oyarzun *et al.* (2007). Similar inputs were used to calculate the actual amount of radiation received on a sloped surface for each hour ($S_{g,h}^*$, $W m^{-2}$), which is required to determine the daily PAR interception fraction (f_{DIPAR}), as described by Oyarzun *et al.* (2007):

$$f_{DIPAR} = \frac{\int_{h=t_{Sr}}^{h=t_{Ss}} [f_{IPAR,h} S_{g,h}^* F_{PAR/Sg}]}{\int_{h=t_{Sr}}^{h=t_{Ss}} [S_{g,h}^* F_{PAR/Sg}]} \quad (5.18)$$

where $F_{PAR/Sg}$ is a fraction of global solar radiation that corresponds to the PAR wavelength range, assumed to be 0.5 (Wang *et al.* 2002).

Table 5.1 summarizes all the input parameters used to model hourly and daily values of fractional photosynthetically active radiation intercepted by the different study orchards. Tree dimensions such as H, B, W_x and W_y , E_x and E_y were all measured with an 8 m calibrated ruler. This was done once every month in order to account for changes in leaf area throughout the growing season. Row orientation was measured with a compass corrected for magnetic declination, and s with a theodolite. Site location data (altitude, latitude, longitude and the standard meridian) was recorded at the study sites using a GPS (Garmin Edge 520, USA).

Hourly and daily fractional PAR interception estimated using the model of Oyarzun *et al.* (2007) were compared to measured values in order to assess the validity of model predictions. Days with expected succession of sunshine and cloudy conditions (generally with global daily solar radiation below 7 MJ m⁻² day⁻¹) were excluded from model simulations due to the fact that the model does not take into account such effects on the variability of predicted f_{IPAR} (Oyarzun *et al.* 2007). Most of these days coincided with daytime rainfall events. These periods totalled 34 out of 756 days for three consecutive growing seasons of mature pecans at Cullinan and 82 out of 732 days for two consecutive growing seasons of macadamias at the White River study site.

Table 5.1 Input parameters used to model hourly and daily values of fractional photosynthetically active radiation intercepted by a closed-canopy pecan orchard in Cullinan, an open-canopy pecan orchard at Hatfield and an open-canopy macadamia orchard at White River.

Input parameters	Experimental orchard		
	37-year-old pecans at Cullinan	7-year-old pecans at Hatfield	6-year-old macadamias at White River
Altitude (m)	1300	137	765
Latitude (°)	-25	-25	-25
Longitude (°)	28	28	31
Standard meridian (°)	30	30	3
Effective fractional canopy cover ($f_{c\text{ eff}}$)	0.51 – 0.98	0.09 – 0.014	0.35 – 0.75
Tree spacing (m)	9 x 9 x 9	10 x 10 ; 10 x 5	8 x 4
Tree height (H, m)	14.5 - 16.0	3.0 - 5.0; 3.0 - 4.5	5.0 - 6.0
Canopy width (W_y , m)	6	5.2 ; 4.8	3.0 - 4.0
Canopy depth (W_x , m)	9	5.7 ; 5.0	4.0 - 7.0
Height of lowest branches (B, m)	0.6 - 2.0	0.8 - 1.4; 1.0 - 1.4	0.6 - 1.0
Canopy porosity (C_P)	0.02 - 0.40	0.30 - 0.45; 0.35 - 0.50	0.10 - 0.20
Row azimuth (Φ_R , °)	20 NNE-SSW	10 N-S; 8 N-S	6 N-S
Slope of the terrain (s, °)	0.2	0.4	1.5

5.2.2.2 Modelling of daily transpiration using the FAO-56 dual crop coefficient approach

In this approach, T is estimated by multiplying values of basal crop coefficients (K_{cb}) by ET_o (Allen and Pereira, 2009). Since T was measured with the heat ratio method throughout the experimental period, transpiration crop coefficients (K_t) were derived instead of K_{cb} . Daily values of K_t were calculated by multiplying the estimated K_t during peak plant growth for conditions having nearly full ground cover ($K_{t\ full}$) with a density coefficient (K_d), which is correlated with the amount of vegetation:

$$K_t = K_d K_{t\ full} \quad (5.19)$$

Daily values of K_d were estimated according to Allen and Pereira (2009) as follows:

$$K_d = \min \left(1, M_L f_{c\ eff}, f_{c\ eff}^{\left(\frac{1}{1+h}\right)} \right) \quad (5.20)$$

where $f_{c\ eff}$ is the effective fraction of ground covered or shaded by vegetation measured near solar noon. Since measurements of $f_{c\ eff}$ were only taken periodically during the experimental period (typically once every two to three weeks), daily estimates of f_{IPAR} were determined using the model of Oyarzun *et al.* (2007); h is the mean plant height in m and M_L is an empirical parameter imposing an upper limit on the relative magnitude of tree T per unit ground area as represented by $f_{c\ eff}$ and attempts to simulate the physical limits of water transport through the plant (Allen and Pereira, 2009). The value of M_L for pecans and macadamias was assumed to be equal to 1.5, as this value was suggested by Allen and Pereira (2009) for other deciduous (almonds, walnut, pistachio and stone fruit) and evergreen (citrus, olives and mangoes) fruit tree species.

Values of $K_{t\ full}$ were calculated as a function of h and adjusted for climate using wind speed (u_2) in $m\ s^{-1}$ and percentage minimum relative humidity (RH_{min}), and the degree of stomatal control on T relative to most agricultural crops in $s\ m^{-1}$ (F_r), as follows:

$$K_{t\ full} = F_r \left(\min(1.0 + 0.1h, 1.2) + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \left(\frac{h}{3}\right)^{0.3} \right) \quad (5.21)$$

F_r was estimated as follows:

$$F_r \approx \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma\left(1 + 0.34u_2 \frac{r_l}{100}\right)} \quad (5.22)$$

where Δ is slope of the saturation vapour pressure versus air temperature curve in kPa °C⁻¹; γ is the psychrometric constant in kPa °C⁻¹; r_l is average leaf resistance for the specific vegetation during the growing season in s m⁻¹. For most agricultural crops the value for r_l , under full cover conditions (assumed to be when the LAI exceeds 3.0 m² m⁻²) is 100 s m⁻¹, which sets F_r to 1. Allen and Pereira (2009) do not suggest any r_l values for pecans and macadamias and therefore average values of r_l for pecans and macadamias during two periods (initial to midseason and end of the season) of the 2010/2011 growing season in each experimental site were estimated by inverting Equation 5.22, after solving for F_r by inverting Equation 5.21, using known daily values of $K_{t \text{ full}}$. $K_{t \text{ full}}$ values were calculated using measured daily K_t and K_d estimated from measured data. The same r_l values were subsequently used to estimate F_r for independent seasons of measurements using Equation 5.22 in order to estimate K_t and T values for model validation purposes.

5.2.2.3 Modelling of daily transpiration using a canopy conductance model

In this approach, T (mm day⁻¹) was estimated as a function of f_{IPAR} of the canopy (dimensionless), daily total solar radiation (R_s , J m⁻² day⁻¹) and vapour pressure deficit (VPD, kPa), following the equation below (Villalobos *et al.* 2013):

$$T = 37.08 \times 10^{-3} \frac{f_{IPAR} R_s}{a + bVPD} \frac{VPD}{P_a} \quad (5.23)$$

where the coefficient 37.08×10^{-3} incorporates the conversion of units of joules of solar radiation to μmol quanta and from mol to kg of H₂O; a ($\mu\text{E mol}^{-1}$) and b ($\mu\text{E mol}^{-1} \text{ kPa}^{-1}$) are the coefficients of the linear function relating $\frac{f_{IPAR} R_s}{g_c}$ to VPD. P_a is atmospheric pressure in kPa. Daytime mean values of bulk canopy conductance (g_c , mm day⁻¹) were calculated by the inversion of the imposed evaporation Equation 4.1.

Daily values of f_{IPAR} were estimated using a successfully parameterized and validated radiation interception model, which was developed by Oyarzun *et al.* (2007). Transpiration data for one growing season at each experimental site was used for model parameterization, which consisted of determining the empirical crop parameters a (which depends on radiation use efficiency) and b (which depends on the crop's stomatal response to VPD), while independent measurements conducted for another season were used for model validation. Analyses for model parameterization and validation excluded days with rainfall (83 out of 488 days for two consecutive growing seasons of pecans and 162 out of 731 days for two consecutive growing seasons of macadamias), as sap flow of wet canopies is reduced substantially and most evaporation occurs directly from the wet surfaces (Villalobos *et al.* 2013).

5.2.3 Sensitivity analyses of daily transpiration modelling input parameters

A sensitivity analysis was conducted for the main input parameters of the following modelling approaches used to estimate daily T of pecans and macadamias: (1) FAO-56 dual crop coefficient approach and (2) the canopy conductance model. The sensitivity analysis consisted of evaluating the estimated output percentage difference when varying each input parameter $\pm 20\%$ of actual input value using the sensitivity index (SI) method as described by Hamby (1994). Input parameter values were varied one-at-a-time, whilst keeping the other parameters constant. This procedure allows a wide range of possible values for each parameter to be evaluated in order to assess true parameter sensitivities:

$$SI = \frac{D_{\max} - D_{\min}}{D_{\max}} \quad (5.24)$$

where D_{\max} and D_{\min} represent the maximum and minimum output values, respectively, resulting from varying the input parameter over its range of possible values. The parameter showing the highest SI value was considered the most sensitive and vice-versa. Table 5.2 shows minimum and maximum possible values considered for each input parameter selected for the sensitivity test.

Table 5.2 Input parameters selected for sensitivity analyses in the different approaches to model daily transpiration.

Model	Model parameter	37-year-old pecans		6-year-old macadamias	
		Min	Max	Min	Max
FAO-56 dual crop coefficient	Limit imposed on water flux (M_L)	1.2	1.8	1.2	1.8
	Mean leaf resistance (r_l)	560	840	760	1140
	Plant height (h)	11	17	4	6
	Basal K_c during peak plant growth ($K_{t \text{ full}}$)	1.0	1.4	0.8	1.2
Canopy conductance	Intercept (a)	800	1200	500	800
	Slope (b)	2000	3100	3000	4400

5.3 RESULTS AND DISCUSSION

5.3.1 Hourly and daily radiation interception modelling

Figure 5.4 depicts hourly f_{IPAR} intercepted by pecan and macadamia trees on completely clear sky days. The proportion of the variance in the simulated values was acceptable in all the study orchards when compared to measured values (coefficient of determination - R^2 varying between 0.62 and 0.77, Singh *et al.* 2005). Model simulations under smaller tree canopies (Figure 5.4B, C and D) had higher R^2 values than those under bigger canopies (Figure 5.4A), which may be explained by the presence of more regular branches and more uniform distribution of leaves within the canopy of smaller trees. In addition, smaller trees have smaller trunks and fewer branches than bigger trees, causing less erroneous data due to reduced shading of the tube solarimeters (Annandale *et al.* 2004). While acceptable R^2 values were obtained in all the orchards considered, the mean absolute percent difference (MAPD) was higher than the reliability criteria of 25% in young pecan trees (Singh *et al.* 2005), which can be attributed to the fact that measured and simulated f_{IPAR} for these trees were generally so small that large mean absolute errors were calculated for small discrepancies between measurements and simulations. The fact that a weighted average f_{IPAR} was calculated for the entire orchard floor, based on measurements conducted at specific positions beneath the canopy might have also contributed to discrepancies between measured and simulated values illustrated in Figure 5.4.

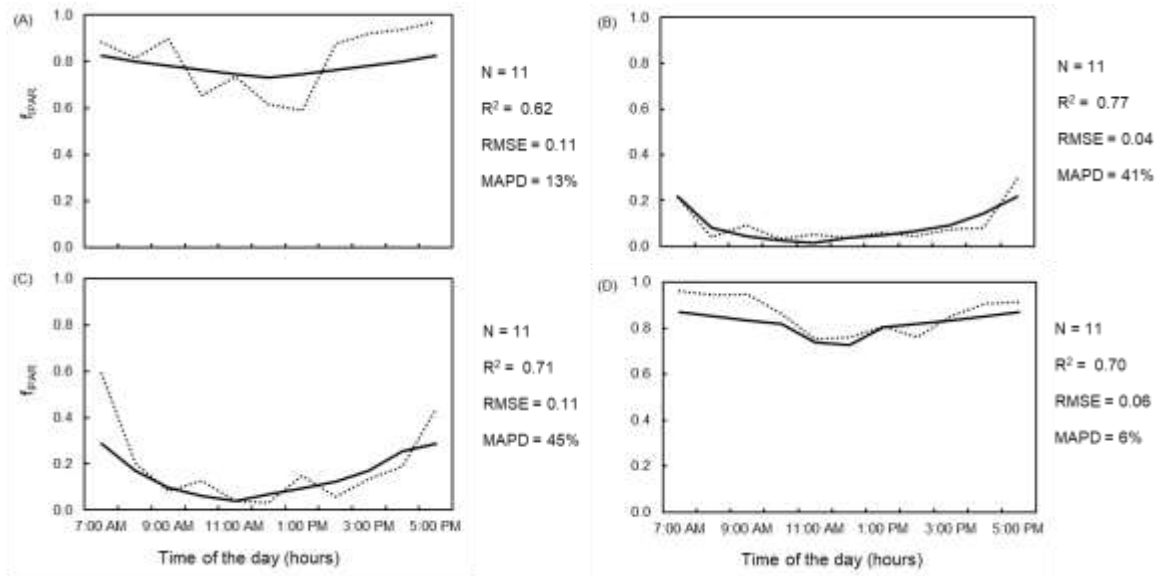


Figure 5.4 Comparison between measured (dotted line) and simulated (solid line) hourly fractional intercepted photosynthetically active radiation (f_{IPAR}) on (A) 25 February 2012 in the 37-year-old pecan orchard at Cullinan, (B) 15 April 2014 in the 7-year-old pecan orchard spaced at 10 m x 10 m at Hatfield, (C) 01 April 2014 in the 7-year-old pecan orchard spaced at 10 m x 5 m at Hatfield and (D) 27 January 2012 in the 6-year-old macadamia orchard at White River.

The performance of the model improved for daily estimations of f_{IPAR} (MAPD varied between 2 and 21% and R^2 between 0.78 and 0.95), which is probably due to compensatory errors in the simulated f_{IPAR} over the course of a day (Figure 5.5). Daily estimated f_{IPAR} values were closer to measured values in trees with bigger canopies (Figure 5.5A and D) compared to those of smaller canopies (Figure 5.5B and C), which is probably due to larger areas of sunflecks on the shaded ground area by trees with smaller canopies, making it difficult to determine representative C_P values.

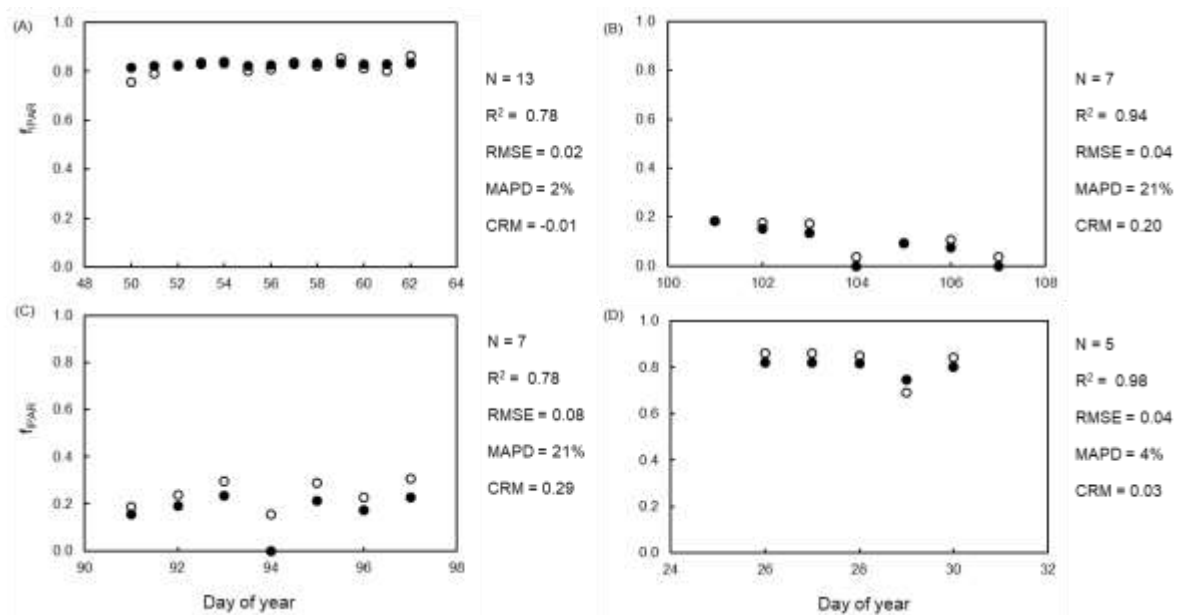


Figure 5.5 Comparison between measured (open circle symbols) and simulated (closed circle symbols) daily fractional intercepted photosynthetically active radiation (f_{IPAR}) for a (A) 37-year-old pecan orchard between 19 February and 12 March 2012, (B) 7-year-old pecan orchard spaced at 10 m x 10 m between 11 and 17 April 2014, (C) 7-year-old pecan orchard spaced at 10 m x 5 m between 01 and 07 April 2014 and (D) 6-year-old macadamia orchard between 26 and 30 January 2012.

Figure 5.6 illustrates simulations of daily changes in f_{IPAR} for a 37-year-old pecan orchard for three consecutive growing seasons in Cullinan. In general, model simulations compared reasonably well with field measurements, except for periods during canopy development (November to December) when the model tended to noticeably under or overestimate f_{IPAR} . Such discrepancy between model predictions and field measurements during the referred period (which coincides with canopy closure) may be explained by the fact that the model uses thermal time to estimate changes in f_{IPAR} of closed-canopy orchards, and various other factors besides thermal time may influence canopy closure. Such factors, in the case of pecan orchards, may include changes in alternate bearing cycles, type and intensity of pruning strategies and fertilization practices. Model predictions were generally good at the end of the season during leaf drop stage, as the result of model extension by taking into account

cumulative thermal time calculated as a function of minimum air temperatures, as suggested by Miyamoto (1983).

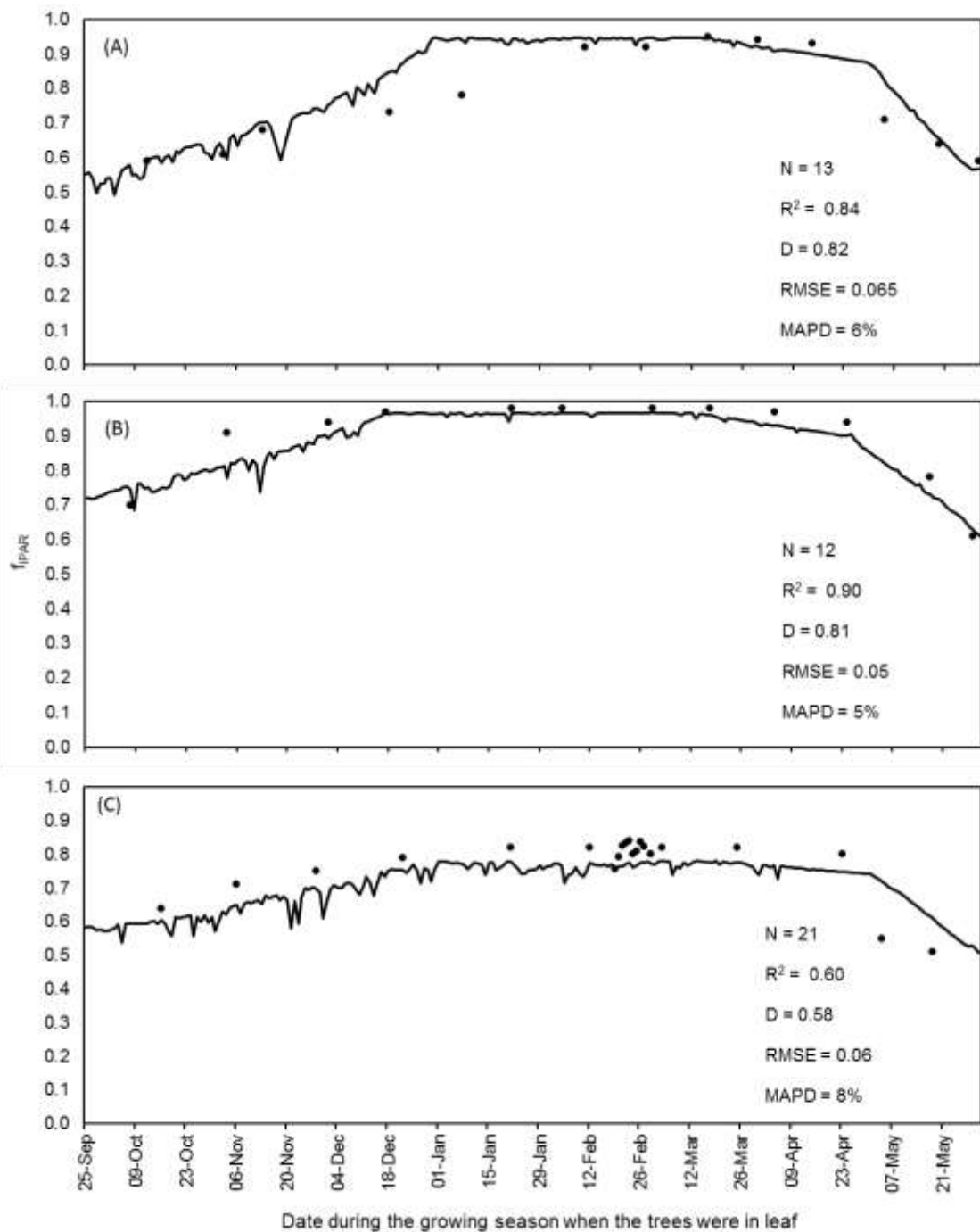


Figure 5.6 Comparison between measured (symbols) and simulated (solid line) daily fractional intercepted photosynthetically active radiation (f_{IPAR}) for a 37-year-old pecan orchard during the (A) 2009/2010 season, (B) 2010/2011 season and (C) 2011/2012 season at the Cullinan study site.

Changes in canopy growth between different growing seasons were more evident in the 37-year-old, closed-canopy pecan orchard (Figure 5.6) compared to the 6-year-old, open-canopy macadamia orchard (Figure 5.7). This is mainly attributable to the pruning strategy employed by the pecan grower. In the closed-canopy pecan orchard, the grower alternated pruning strategies as follows: 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 implemented, whilst in 2011/2012 heavy mechanized hedge pruning and top pruning were carried out. In the open-canopy macadamia orchard, on the other hand, the trees were pruned similarly in both growing seasons (2010/2011 and 2011/2012) using a modified central leader pruning strategy prior to the start of each season, where selected limbs were removed to improve light interception by the canopy. Such distinct pruning strategies between pecans and macadamias may be typical in deciduous and evergreen tree nut crops at relatively high levels of canopy cover. As observed in Figure 5.7, the canopy growth of macadamia trees was slightly higher in the 2011/2012 season (seasonal average $f_{IPAR} = 0.60$) than in the 2010/2011 season (average $f_{IPAR} = 0.55$), which helps explain the marginally higher seasonal T in the 2011/2012 season (total of 480 mm) as compared to the 2010/2011 season (total of 452 mm).

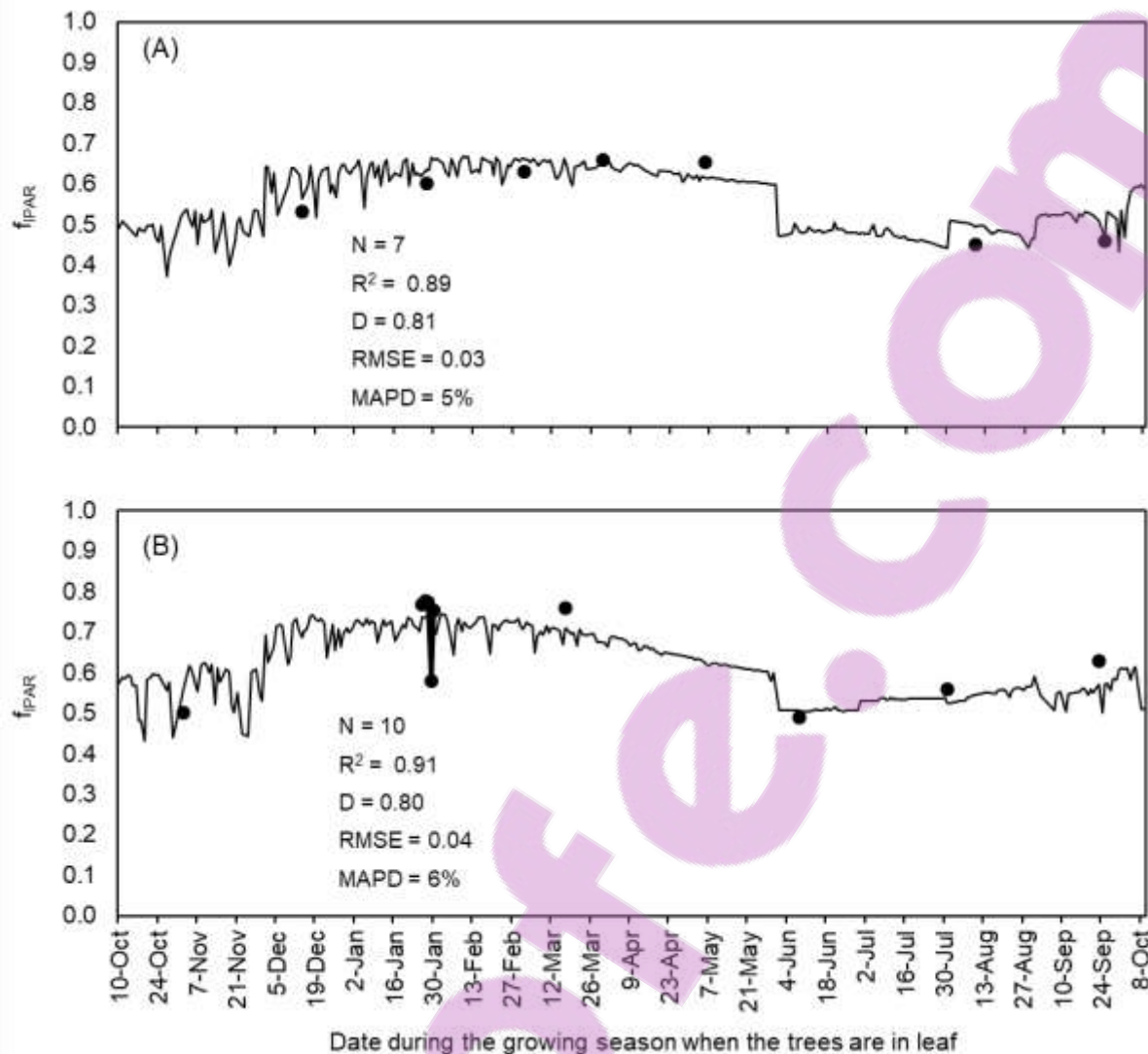


Figure 5.7 Comparison between measured (symbols) and simulated (solid line) daily fractional intercepted photosynthetically active radiation (fIPAR) for a 6-year-old macadamia orchard during the (A) 2010/2011 season and (B) 2011/2012 season at the White River study site.

5.3.2 Daily transpiration estimates using the FAO-56 dual crop coefficient procedure

The FAO-56 procedure for estimating transpiration coefficients (K_t), as a function of fraction of ground cover, crop height and the degree of stomatal control exhibited by the crop is applicable to crops grown under non-limiting soil water supply conditions. As a result, this section will only include measurements and simulations conducted for

the 37-year-old, closed-canopy pecan orchard and the 6-year-old, open-canopy macadamia orchard. The FAO-56 procedure used in this study was improved by making use of daily f_{IPAR} estimates obtained as described in Section 5.2.2.1. Figures 5.8 and 5.9 illustrate parameterization and validation of the FAO-56 model through a comparison between daily measured and simulated values of K_t and T for the 37-year-old pecan orchard.

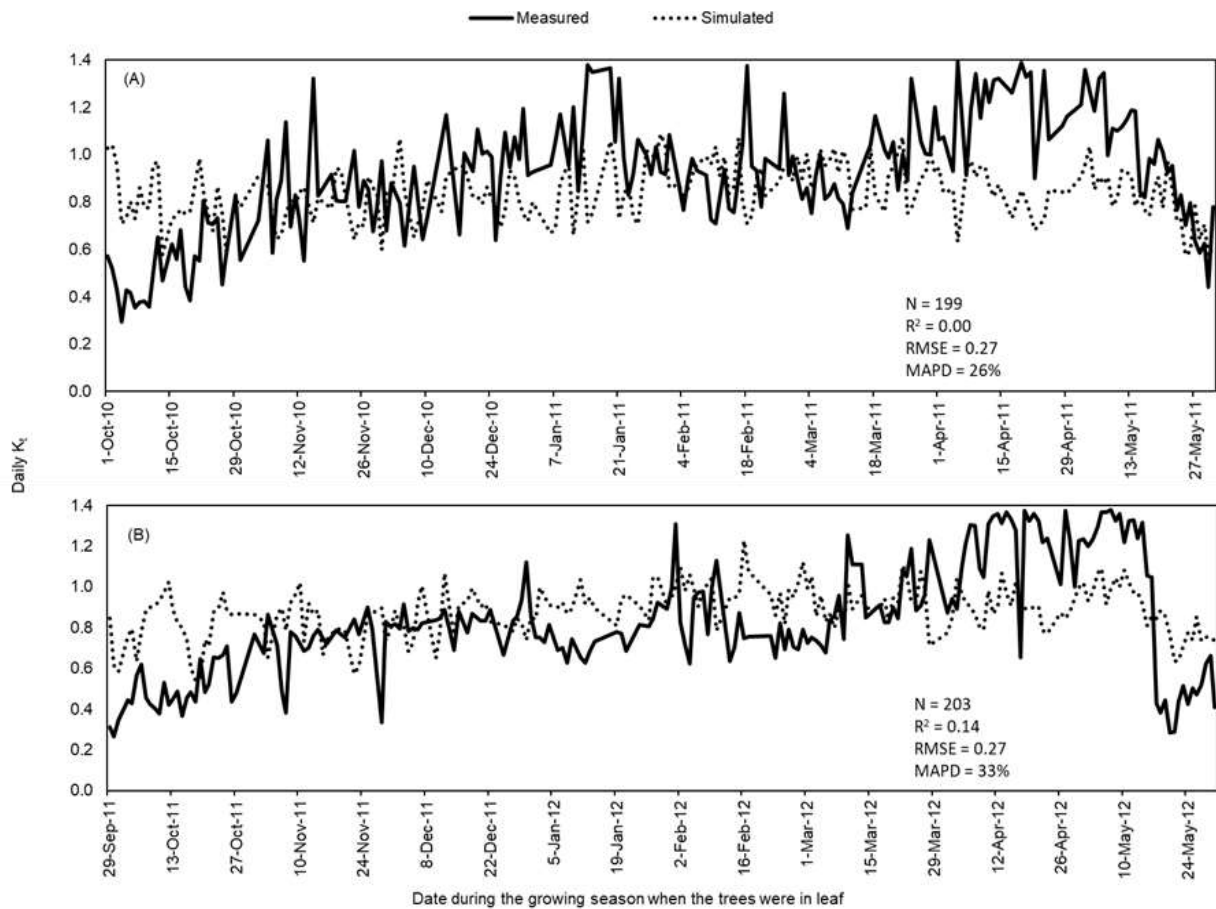


Figure 5.8 Comparison between daily measured and simulated transpiration crop coefficients (K_t) for the 37-year-old pecan orchard for (A) parameterization and (B) validation of the FAO-56 model.

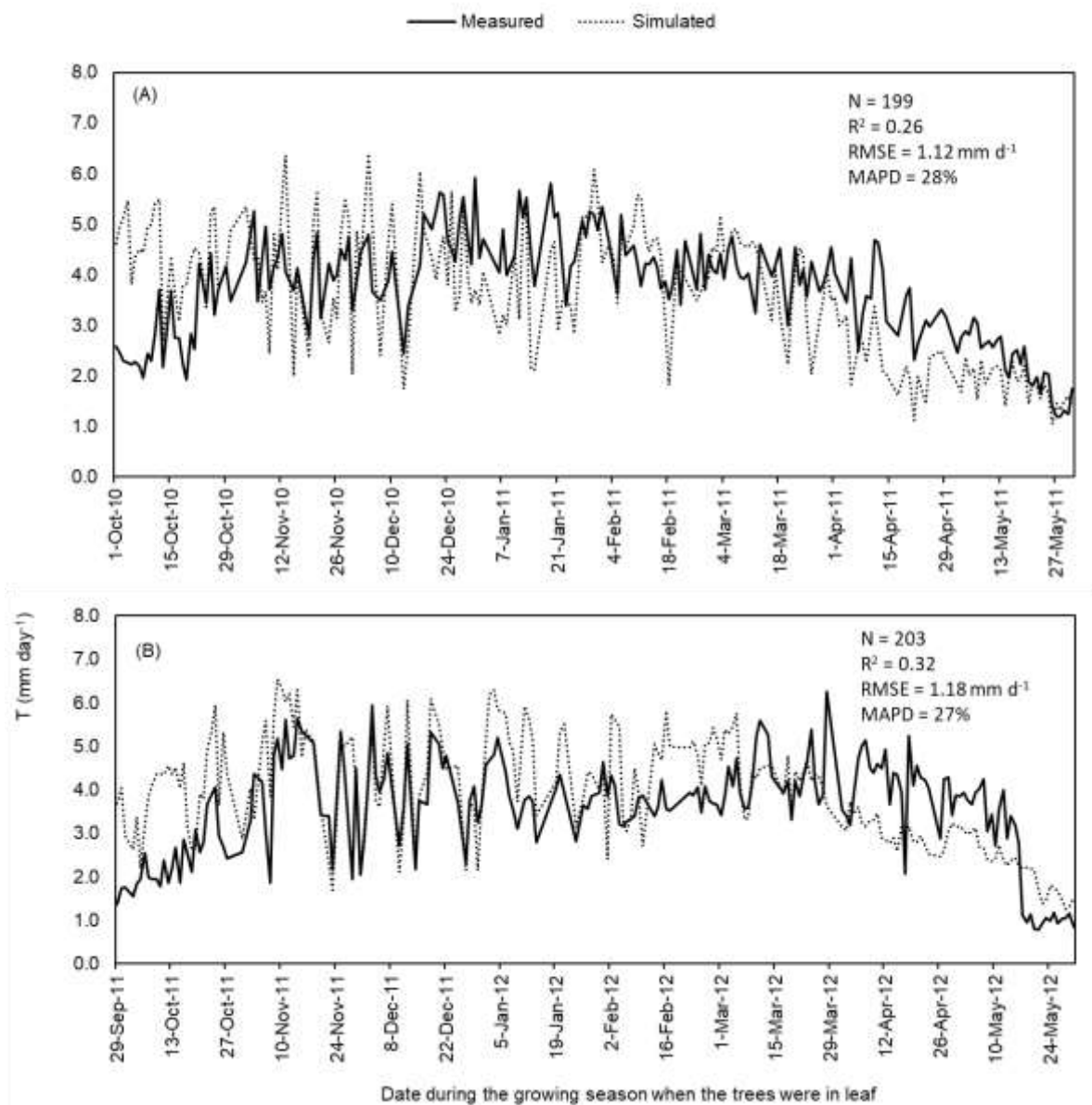


Figure 5.9 Comparison between daily measured and simulated transpiration (T) for the 37-year-old pecan orchard for (A) parameterization and (B) validation of the FAO-56 model.

As observed from Figures 5.8 and 5.9, the FAO-56 model was not well parameterized or validated for estimating daily K_t and T of pecans throughout the growing season. The standard deviation of residuals (measured by RMSE) was quite high in the two data sets used for model evaluation, indicating that the data points were not well concentrated around the line of best fit. Other statistical parameters, such as R² and MAPD were also outside the criteria of acceptability for model validation. Poor

performance of the FAO-56 model is also observed in Figures 5.10 and 5.11 for the estimation of daily K_t and T of macadamias (RMSE > half the standard deviation of the measured data and R^2 below 0.5).

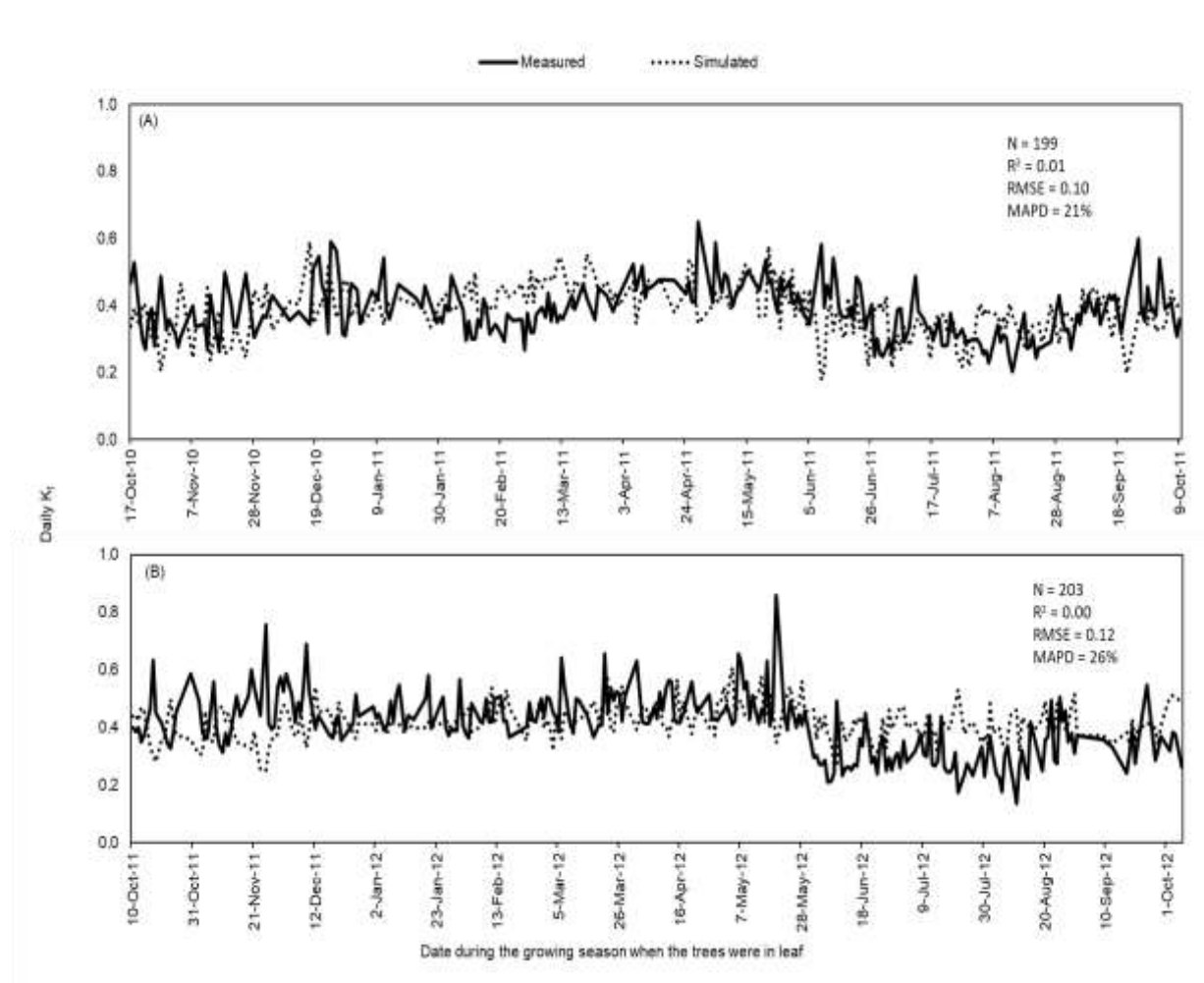


Figure 5.10 Comparison between daily measured and simulated transpiration crop coefficients (K_t) for the 6-year-old macadamia orchard for (A) parameterization and (B) validation of the FAO-56 model.

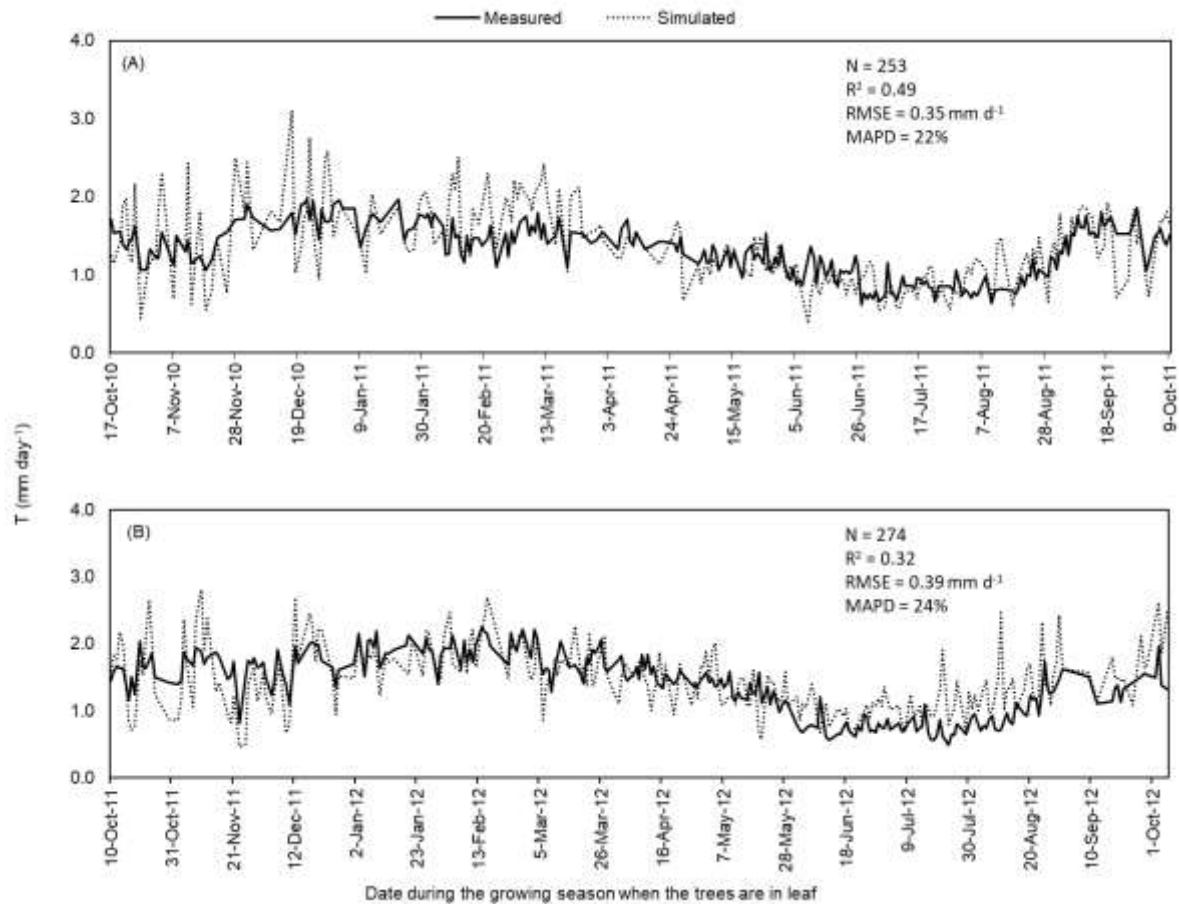


Figure 5.11 Comparison between daily measured and simulated transpiration (T) for the 6-year-old macadamia orchard for (A) parameterization and (B) validation of the FAO-56 model.

For both the pecans and macadamias, noticeable discrepancies between measured and simulated values of daily K_t and T can mainly be attributable to the use of r_i values that are only an approximate estimate for r_i . This is due to the fact that r_i is derived by inverting Equations 5.21 and 5.22, which contain artefacts of the $K_{t\text{ full}}$ measurements, weather data errors and the constructs of the two equations (Allen and Pereira, 2009). Besides, only two single average r_i values were used to simulate K_t and T for the entire growing season of pecans ($r_i = 700 \text{ s m}^{-1}$ for initial and midseason stages and 900 s m^{-1} for end of season) and macadamias ($r_i = 900 \text{ s m}^{-1}$ for initial and midseason stages and 950 s m^{-1} for end of season), as suggested by Allen and Pereira (2009). This may not be representative under all possible conditions of climate and vegetative growth. Such high r_i values found for pecans and macadamias in this study

are not surprising, as similar magnitudes for the r_l parameter were suggested by Allen and Pereira (2009) for olives ($r_l = 950 - 1000 \text{ s m}^{-1}$), pistachios ($r_l = 300 - 700 \text{ s m}^{-1}$) and walnuts ($r_l = 180 - 800 \text{ s m}^{-1}$). The actual values of the parameter r_l calculated on a daily basis varied considerably as illustrated in Figure 5.12 for 37-year-old mature pecans in the 2010/2011 and 2011/2012 growing seasons.

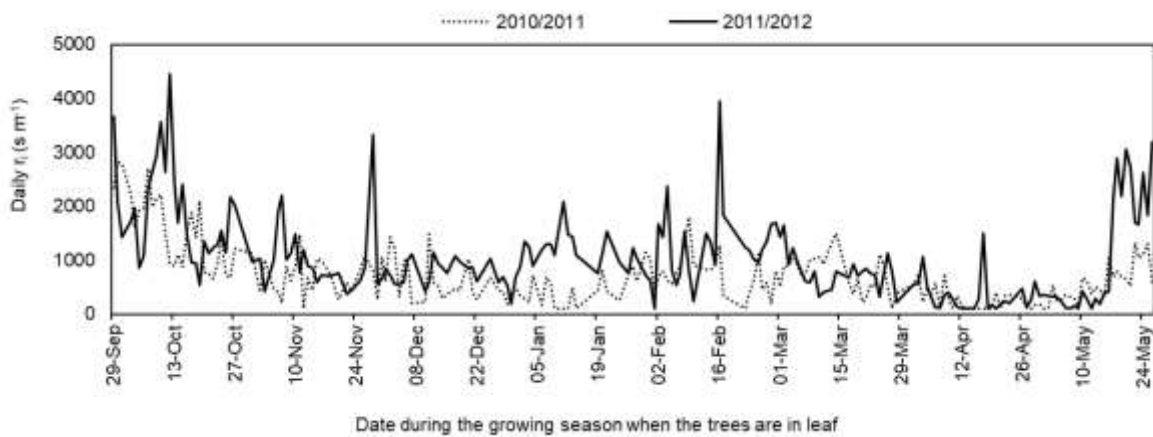


Figure 5.12 Daily leaf resistance (r_l) parameter of a 37-year-old, closed-canopy pecan orchard during the 2010/2011 and 2011/2012 growing seasons.

As evident in Figure 5.12, daily values of the r_l parameter for pecans varied from 100 to 2700 s m^{-1} in the 2010/2011 and from 100 to 4200 s m^{-1} in the 2011/2012 growing season. Higher r_l values in 2011/2012 are possibly due to lower K_t values (average $K_t = 0.84$ during the study period) as compared to the 2010/2011 season (average $K_t = 0.92$). This can be explained by lower total T (721 mm) and higher total ET_o (894 mm) during the 2011/2012 season as compared to the previous season ($T = 737$ mm and $ET_o = 847$ mm). Low measured K_t values as a result of decreased T on days with high ET_o was the main reason for increased discrepancies between measured and predicted daily T values using the FAO-56 dual crop coefficient model, as on these days the calculated r_l parameter was noticeably high. Findings from this study, presented and discussed in Chapter 4, revealed that under conditions of high atmospheric evaporative demand, T of pecans and macadamias is limited, which is possibly due to increased stomatal control over T , leading to increased stomatal resistance as a result of reductions in leaf water potentials. This possibly occurs to prevent water potentials from dropping to levels which could cause embolism

formation. Limited T under conditions of high ET_o were also observed in irrigated citrus crops (Marin and Angelocci, 2011; Taylor *et al.* 2015). Since the FAO-56 dual crop coefficient model uses two single average r_i value to estimate T for the entire growing season, the model tends to overestimate T on days with high ET_o , when increased canopy resistances are expected to occur. The same limitation of the FAO-56 model, as the result of using one single r_i value, was also observed in citrus, causing poor estimations of T (Taylor *et al.* 2015). When r_i values were determined for each month during the growing season, these authors found more accurate estimates of monthly totals of T. Another possible reason for noticeable discrepancies between predicted and measured daily T values for pecans and macadamias may be attributable to the use of wind speed as one of the most important atmospheric variables influencing predicted T, while it was observed in this study that T of pecans and macadamias is primarily driven by VPD, followed by solar radiation. The contribution of these variables are accounted for indirectly in the estimation of T, through the calculation of ET_o . Therefore, modelling procedures which use VPD and solar radiation directly may be more appropriate to estimate T of pecans and macadamias.

Thus, a more mechanistic crop modelling approach should be considered, which predicts that T does not always increase at the same rate as the atmospheric evaporative demand and includes VPD and solar radiation as modelling inputs to predict T. Such an approach should be able to model canopy resistance in order to improve estimates of T on a shorter time scale. This can be addressed using a canopy conductance modelling approach, as presented and discussed in the next section.

5.3.3 Daily transpiration estimates using a canopy conductance model

The canopy conductance model used in this study is based on a simplified version of the equation of Leuning (1995) at the canopy level, which assumes that canopy assimilation is proportional to radiation interception (Villalobos *et al.* 2013). Based on this assumption, coefficients from linear regressions of the ratio of intercepted radiation and canopy conductance as a function of VPD were developed for different fruit tree species. Villalobos *et al.* (2013) reported regression coefficients for oranges, walnuts, apples, olives, apricots, peaches and pistachios. This study extends this information by including regression coefficients for pecans and macadamias (Table

5.3). The 2010/2011 growing season of pecans and macadamias was used for model parameterization, while the subsequent 2011/2012 season was used for model validation.

As indicated in Table 5.3, the ratio a/b which equals D_o , relates crop response (stomatal closure) to an increase in VPD. Based on the model of Leuning (1995), the parameter D_o is inversely proportional to the sensitivity of canopy conductance to VPD, in other words, a decrease in the parameter D_o will result in decreased canopy conductance with increased VPD. In this study, both tree nut crops showed low values of D_o (0.15 – 0.38), similar to those reported by Villalobos *et al.* (2013) for apricots, apples, peaches and pistachios ($D_o = 0.22$ to 0.58), suggesting stomatal closure with increased VPD, as seen in Chapter 4 of this study for pecans and macadamias where daily T rates considerably decreased at $VPD > 1.2 - 1.4$ kPa. These results confirm, once again, a high degree of coupling of T to the atmosphere in pecans and macadamias ($\Omega = 0.16$ to 0.22) which was observed in this study and presented in Chapter 4.

Table 5.3 Regressions of the ratio of intercepted radiation and canopy conductance versus vapour pressure deficit. The intercept (a) and slope (b) of the linear regression equations are also shown, including the empirical coefficient D_o calculated as the ratio a/b , which relates the response of stomatal closure to vapour pressure deficit. The root mean square error (RMSE) of the simulated transpiration versus the observed one (mm day^{-1}) is also presented.

Tree nut crop	a ($\mu\text{E mol}^{-1}$)	b ($\mu\text{E mol}^{-1} \text{kPa}^{-1}$)	R^2	n	D_o	RMSE (mm day^{-1})
Pecans	1029	2600	0.84	199	0.49	0.71
Macadamias	650	3700	0.82	253	0.18	0.27

The simplified canopy conductance model developed by Villalobos *et al.* (2013) for estimation of daily T was successfully parameterized and validated for pecans and macadamias (Figures 5.13 and 5.14). Adequate predictions of daily T were obtained for both model parameterization for pecans ($R^2 = 0.57$ and MAPD = 15%) and macadamias ($R^2 = 0.60$ and MAPD = 17%), as well as model validation ($R^2 = 0.54$ and MAPD = 21% for pecans and $R^2 = 0.64$ and MAPD = 20% for macadamias). Model predictions considerably improved using the canopy conductance model as compared to the FAO-56 model, for both pecans (R^2 values increased from 0.26 – 0.32 to 0.54 – 0.57 and MAPD decreased from 27 – 28% to 15 - 21%) and macadamias (R^2 values increased from 0.32 – 0.49 to 0.60 – 0.64 and MAPD decreased from 22 – 24% to 17 - 20%).

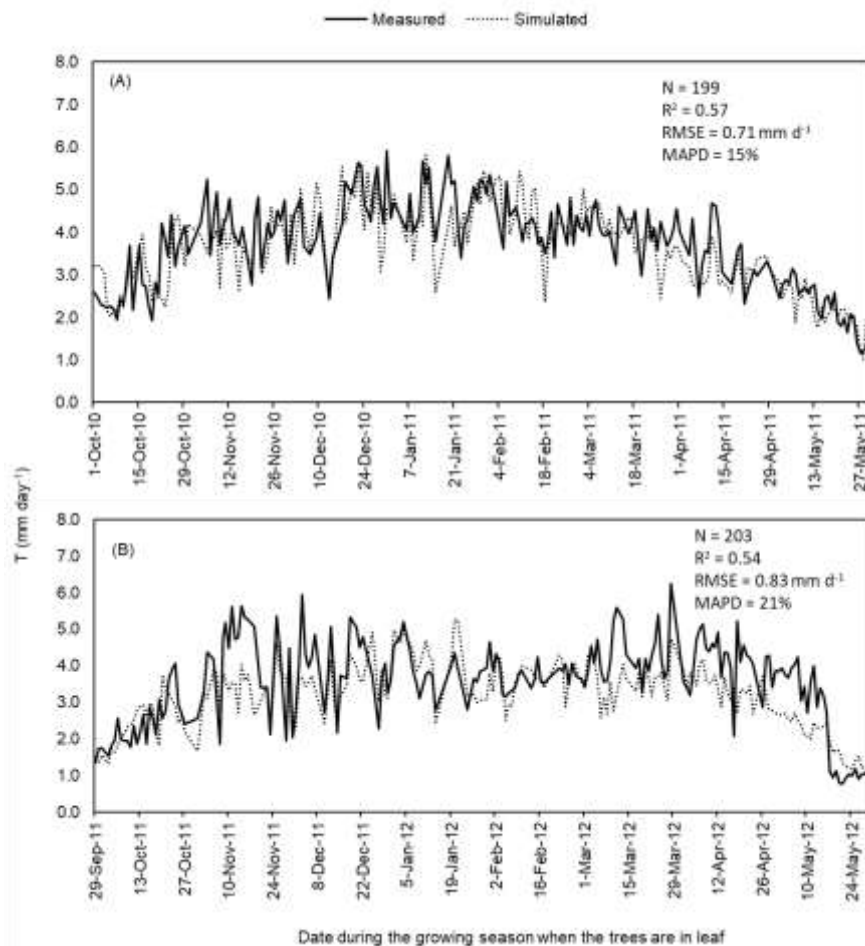


Figure 5.13 Comparison between daily measured and simulated transpiration (T) for the 37-year-old pecan orchard for (A) parameterization and (B) validation of the canopy conductance model.

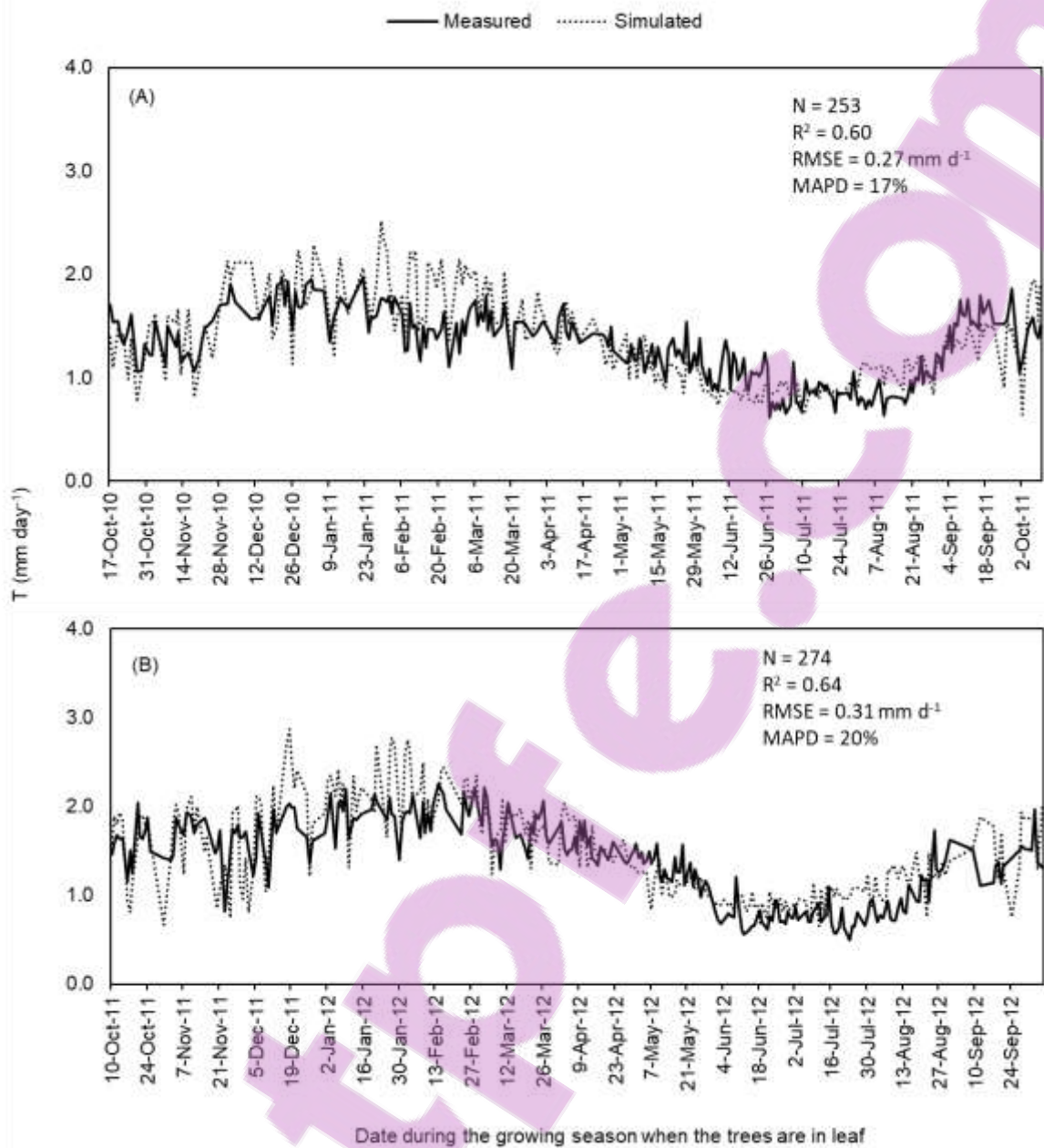


Figure 5.14 Comparison between daily measured and simulated transpiration (T) for the 6-year-old macadamia orchard for (A) parameterization and (B) validation of the canopy conductance model.

The improvement in daily predictions of T using the canopy conductance model of Villalobos *et al.* (2013) is mainly attributable to the fact that this is a more mechanistic approach which increases precision of daily T estimates using fewer atmospheric variables (VPD and solar radiation) relative to the FAO-56 model which also requires

wind speed (Allen and Pereira, 2009; Villalobos *et al.* 2013). As discussed in Chapter 4, VPD, followed by solar radiation are the most important atmospheric variables controlling T of pecans and macadamias. Besides, the parameterization of the canopy conductance model of Villalobos *et al.* (2013) enables the determination of specific crop coefficients **a** and **b**, which account for the manner in which canopy conductance is regulated in proportion to changes in atmospheric CO₂ concentration and radiation use efficiency. Although crop specific leaf resistance values are also obtained with the FAO-56 approach through model parameterization, the model uses two single average values of the leaf resistance parameter (one for the initial and midseason stages and another one for end-season stage) to estimate daily T throughout the entire season, causing overestimation of T on days with high ET_o. The simplified canopy conductance model of Villalobos *et al.* (2013), on the other hand, predicts that the increase in T slows down as VPD increases. Modelling such physiological behaviour is important for fruit tree species, as it has been observed in selected species such as citrus and olives, that T remains reasonably constant under conditions of increasing atmospheric evaporative demand, even when trees are well-watered (Villalobos *et al.* 2000; Taylor *et al.* 2015). Similar behaviour has also been noted for well-watered pecans and macadamias in this study, using a quantile regression approach to analyse daily T data measured for two to three consecutive growing seasons at the study sites, as presented in Chapter 4, Section 4.3.4.

Under conditions of high ET_o, the canopy conductance model of Villalobos *et al.* (2013) predicted T of pecans and macadamias reasonably well when daytime VPD was high, but considerably overestimated T under low daytime VPD values. The overestimated T was more evident for macadamias than for pecans (Figure 5.14A and B, generally in January to February of both growing seasons). This could be the result of climatic differences between the two study sites, as well as differences in crop response to changes in VPD. Daily changes in ET_o were more proportionally related to fluctuations of daytime VPD at Cullinan as compared to White River (data not shown) and a restriction in daily T was observed for macadamias at a lower VPD threshold (1.2 kPa) compared to pecans (1.4 kPa), as discussed in Chapter 4.

Better performance of the canopy conductance model of Villalobos *et al.* (2013) was observed when T was predicted on a 7 or 14-day time steps, as opposed to a daily

time step (Figures 5.15 and 5.16). Such time steps can potentially aid with scheduling irrigation of micro-sprinkler or flood irrigated orchards, where irrigation events typically occur once weekly or biweekly, which is the case of various pecan orchards in South Africa and New Mexico. A seven or 14-day time steps can also aid in forecasting irrigation schedules for macadamia and pecan growers in the short-terms.

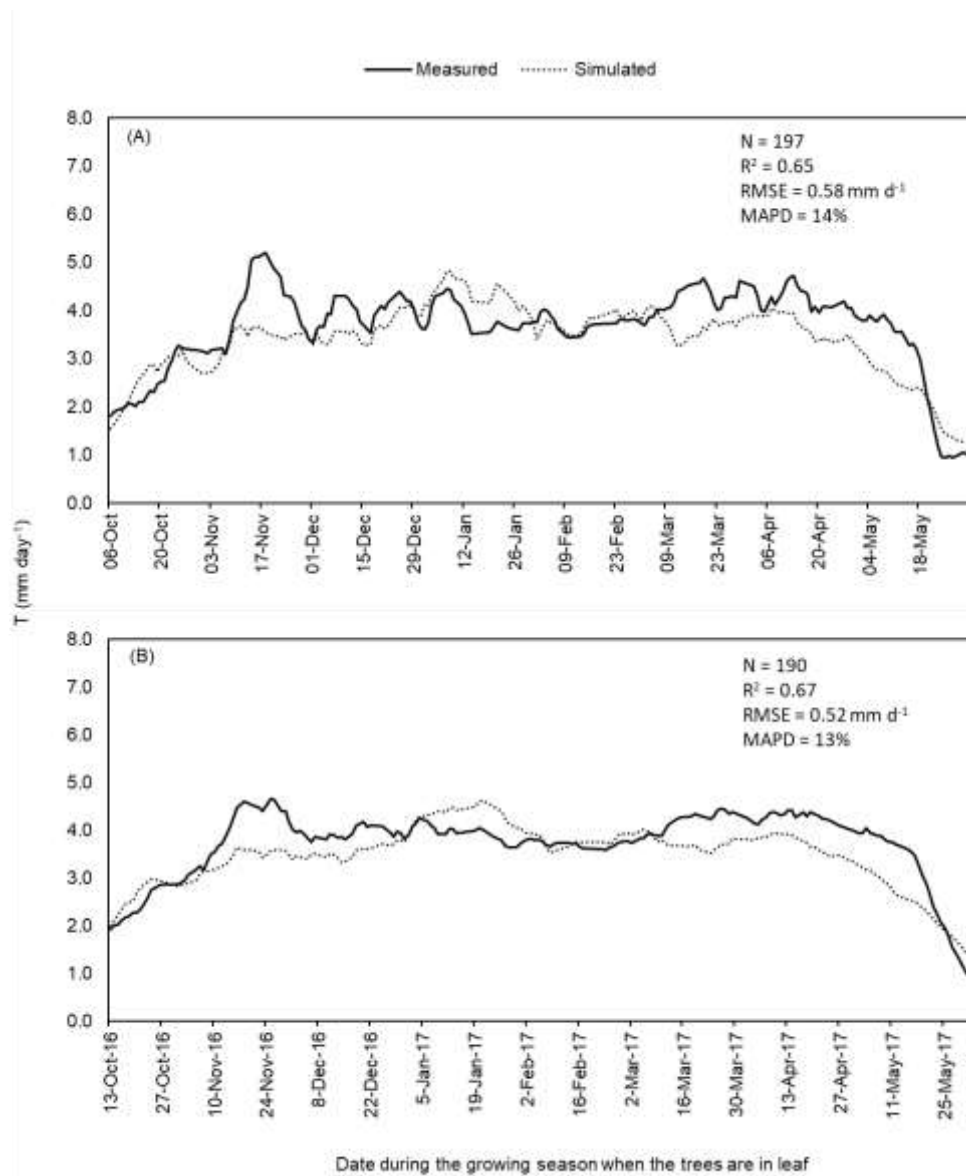


Figure 5.15 Running average daily transpiration (T) of the well-watered pecan orchard during the 2011/2012 growing season estimated using the canopy conductance model on a (A) seven and (B) 14-day time step at the Cullinan study site.

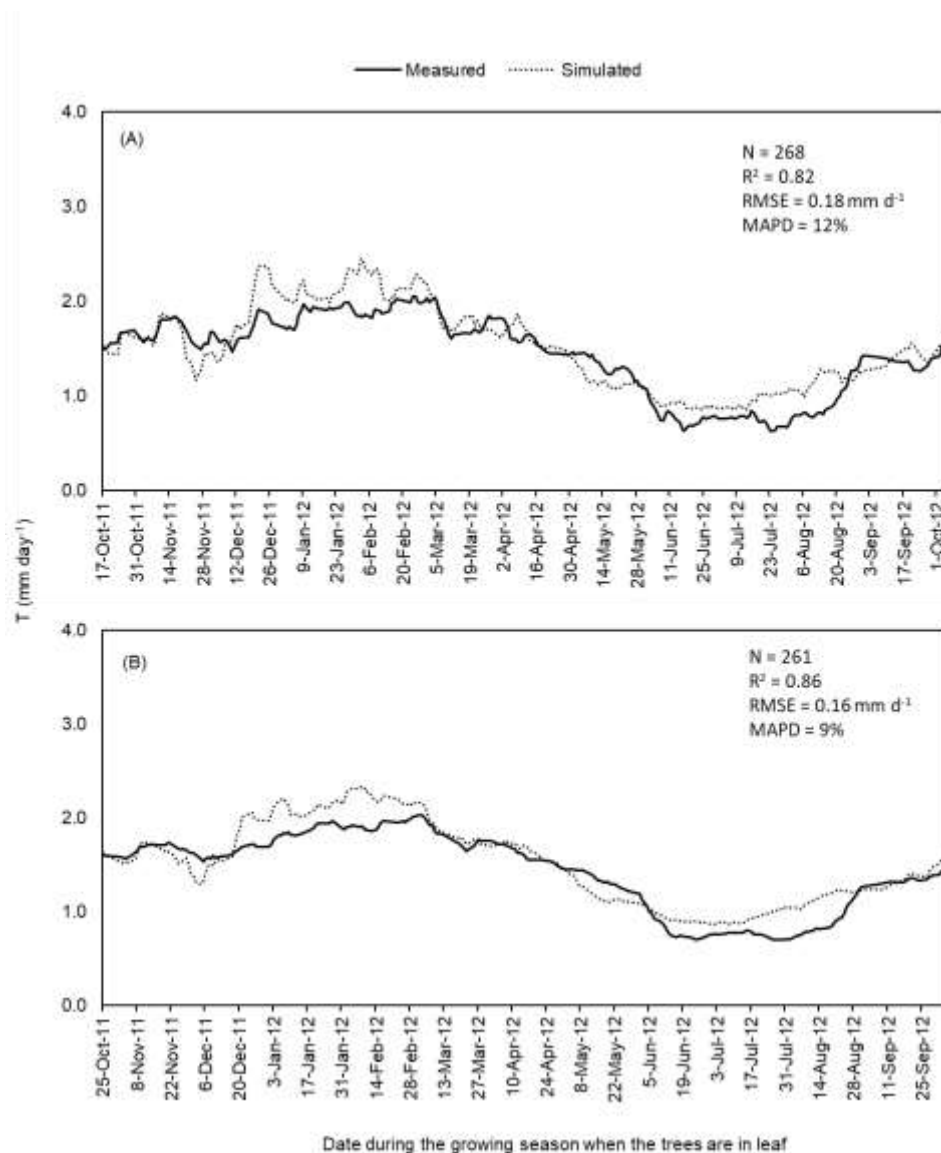


Figure 5.16 Running average daily transpiration (T) of well-watered macadamia trees during the 2011/2012 growing season estimated using the canopy conductance model on a (A) seven and (B) 14-day time step at the White River study site.

5.3.4 Sensitivity analyses for the FAO-56 and canopy conductance transpiration models

Various crop parameters affecting modelled T were selected for sensitivity analyses in both modelling approaches tested in this study, as follows:

- FAO-56 model: M_L which imposes an upper limit on the relative magnitude of T per unit of ground area as represented by the effective fraction of ground

covered by vegetation; $K_{t \text{ full}}$ which is the estimated basal K_c during peak plant growth for conditions having nearly full ground cover; r_l which is a mean leaf resistance parameter for the vegetation in question, and h which is mean plant height.

- Canopy conductance model: parameters **a** and **b**, which are the coefficients of the linear function relating $\frac{f_{IPAR} R_{sd}}{g_c}$ to changes in VPD.
- Parameter f_{IPAR} used account for changes in canopy growth in both modelling approaches.

Table 5.4 shows the results of the sensitivity analysis on seasonal predicted T during the growing season 2011/2012 of pecans and macadamias.

Table 5.4 Sensitivity analysis results on seasonal transpiration predicted using the FAO-56 and canopy conductance models.

Model	Parameter	Sensitivity index (SI, %)	
		37-year-old pecans	6-year-old macadamias
FAO-56	M_L	13	19
	r_l	16	16
	h	0.6	1.2
	$K_{t \text{ full}}$	20	29
	f_{IPAR}	14	21
Canopy conductance	a	13	8
	b	43	36
	f_{IPAR}	30	33

The sensitivity analysis presented in Table 5.4 indicates that both the FAO-56 and canopy conductance models have highly sensitive input parameters which are required for the estimation of daily T. However, the canopy conductance model requires fewer highly sensitive input parameters (**a** and **b** coefficients) than the FAO-56 model (M_L , r_l and $K_{cb \text{ full}}$). In addition, the **a** and **b** coefficients required in the canopy conductance model can be directly determined through linear regression of $\frac{f_{IPAR} R_{sd}}{g_c}$ against VPD, whilst the M_L parameter in the FAO-56 model can only be modified to fit the specific vegetation using an iterative search procedure (Paço *et al.*

2012) or using the values published by Allen and Pereira (2009) for other deciduous and evergreen fruit tree species, which may only be an estimate of the actual M_L parameter for each specific crop. Moreover, the **a** and **b** coefficients in the canopy conductance model are quite conservative, as seasonal averages can be used to estimate daily T reasonably well throughout the entire season and between seasons for each crop species. On the other hand, the r_1 parameter in the FAO-56 model is highly sensitive to changes in climate and vegetative growth, thus requiring short time-step estimates (monthly averages at least) to produce accurate predictions of T (Taylor *et al.* 2015). These monthly average r_1 values also tend to be orchard specific, and as a result, they may need to be adjusted to specific conditions of climate and orchard management prior their use for K_t and T estimates (Taylor *et al.* 2015). Accurate estimates of f_{IPAR} are, however, required in both modelling approaches in order to obtain acceptable estimates of daily T . This is particularly evident for the canopy conductance model, which is not surprising as PAR directly influences canopy stomatal conductance regulation and T (Wehr *et al.* 2017). Nevertheless, all the comparative advantages mentioned above with the use of the canopy conductance model of Villalobos *et al.* (2013) make it a more suitable modelling approach to estimate daily T of fruit tree species under a wide range of climates and orchard management practices provided that model parameterization is done for each species.

5.4 CONCLUSIONS

A simple model to predict radiation interception by fruit tree orchards was successfully validated in this study to simulate hourly and daily radiation interception by pecan trees planted in a triangular or rectangular pattern, as well as by hedgerow planted macadamia trees. The model required few and relatively easy-to-obtain input parameters. The modelling procedure was improved by including canopy porosity estimates for mature trees using a thermal time approach, similar to that used for simulation of canopy development in vineyards, but slightly modified in this study to predict the increase in canopy porosity during leaf drop for deciduous fruit tree species. Hourly and daily fractional PAR intercepted by young and mature trees compared quite well to measured values.

Daily fractional intercepted PAR estimates throughout the growing season were used to predict daily transpiration of pecans and macadamias using two different modelling approaches, namely the modified FAO-56 dual crop coefficient approach and a canopy conductance model. Model performance evaluation revealed poor estimates using the FAO-56 crop coefficient model for both pecans and macadamias. This was mainly attributable to strong stomatal conductance regulation in these tree nut species, which causes a reduction in the rate of increase in transpiration relative to the atmospheric evaporative demand. This implies that the use of two single average mean leaf resistance parameters to estimate daily transpiration for the entire season would not be sufficient for accurate predictions of transpiration.

When testing a simple canopy conductance model, good estimates of daily transpiration were obtained for both, pecans and macadamias. The canopy conductance model was successfully parameterized using daily transpiration measured during the 2010/2011 growing season of pecans and macadamias and validated using the subsequent growing season in 2011/2012. Its good performance was, however, very dependent on appropriate estimates of daily fractional interception of PAR and determination of correct crop parameters for each tree species. If these requirements are met, this modelling approach shows great potential to aid with irrigation scheduling of a wide range of fruit tree orchards, assist scientists and researchers with better understanding of crop water use dynamics and relations, and policy makers manage water resources supply more efficiently on shorter periods. Accurate estimates of transpiration may enable fruit tree growers and researchers to better evaluate alternative options for water savings by providing estimates of the effective amount of water used by the crop, which will encourage growers to use irrigation systems that are more efficient, where the component of soil evaporation can be reduced or suppressed. Alternatively, other effective orchard management practices should be encouraged by growers to minimize soil evaporation. This will require an understanding of the process of soil evaporation in orchard crops and its quantification under various management scenarios as presented in the next chapter.

CHAPTER 6: SOIL EVAPORATION IN PECAN AND MACADAMIA ORCHARDS

6.1 INTRODUCTION

Quantification of soil evaporation (E_s) from cropped fields is frequently needed to compute energy and water balances for improved crop water use efficiency and water management practices of cropping systems (Daamen *et al.* 1993; Bonachela *et al.* 2001; Kool *et al.* 2014). Instantaneous measurements of E_s are also important for the development and validation of E_s prediction models, as well as for validation of other E_s measurement methods (Ham *et al.* 1990). The E_s component can form a significant part of crop evapotranspiration (ET) in fruit tree orchards, particularly at young planting stages and under conditions of high-frequency irrigation, although high proportions of E_s have also been reported in mature orchards as a result of intensive pruning practices (Bonachela *et al.* 1999). Research studies conducted on irrigated olive orchards showed approximately 30% of the total ET as E_s for a sprinkler irrigated, mature orchard with 36% ground cover (Bonachela *et al.* 1999) and up to 43% of ET for a young, drip irrigated orchard with 5% ground cover (Bonachela *et al.* 2001). Thus, a number of factors influence the variability of E_s including crop age, type of irrigation system and wetting frequency, weather variables, crop growth period, soil texture, crop type and planting patterns (Wang and Liu, 2007).

Soil evaporation measurements under a crop canopy are often conducted using micro-lysimeters, also called mini-lysimeters or evaporimeters, which are made from PVC tubing, with typically a diameter of 7 to 20 cm with a length of 7 to 30 cm, into which surface soil is placed (Gregory, 1991; Daamen *et al.* 1993; Jara *et al.* 1998; Bonachela *et al.* 1999; Bonachela *et al.* 2001; Wang and Liu, 2007; Paço *et al.* 2012; Kool *et al.* 2014; Zhao *et al.* 2015). Micro-lysimeters are, therefore, small isolated volumes of bare soil (typically 1 – 3 kg) that are frequently removed from the soil surface where they are installed, and weighed to determine water loss (Daamen *et al.* 1993). This simple technique provides reliable and affordable measurements of E_s , with minimum alteration of the soil surface (Jara *et al.* 1998). However, this technique also presents few drawbacks regarding the amount of time it requires to make the measurements,

its inability to measure evaporation immediately after irrigation or rain, limited representation of field conditions due to small sample size and constraints in time resolution as a result of manual weighing (Kool *et al.* 2014).

Despite the limitations described above, accurate measurements of E_s are possible using micro-lysimeters, provided that precautions are taken to replace core samples within the lysimeter regularly (depending on the frequency of irrigation or rainfall events), in order to maintain a similar soil water status to the surrounding soil (Daamen *et al.* 1993; Wang and Liu, 2007). In addition, care should be taken to extract soil core samples with minimum disturbance, to ensure termination of root extraction of water from the soil core once it is isolated in the micro-lysimeter, to choose appropriate material to build the micro-lysimeters (normally made of PVC pipe), which limits conduction of heat through the micro-lysimeter casing, to use lysimeters and liners with internal diameters ≥ 5 cm and length ≥ 10 cm, as well as to seal the base of the lysimeter prior to its placement using water proof tape and a thin metal base plate (Daamen *et al.* 1993; Evett *et al.* 1995). In addition, all the details of field measurements of E_s should be well documented in order to illustrate the accuracy of measurements and to show their representativeness (Allen *et al.* 2011a).

Soil evaporation beneath a canopy or in between plants is often predicted using the FAO-56 dual crop coefficient method, by estimating the amount of energy at the soil surface in conjunction with energy consumed by transpiration (Allen *et al.* 1998; Allen, 2000; Allen *et al.* 2005; Er-Raki *et al.* 2007; Er-Raki *et al.* 2008; Er-Raki *et al.* 2010; Li *et al.* 2010; Liu and Luo, 2010; Rosa *et al.* 2012b; Pereira *et al.* 2015). The functional approach of this model is similar to the model of Ritchie (1972), in which the E_s process is modelled in two separate stages: an energy limiting stage and a falling rate stage. Other E_s modelling approaches include the Shuttleworth–Wallace model, which is based on Penman-Monteith resistance equations (Zhao *et al.* 2015) and the soil – atmosphere coupled model, which is constructed from a set of equations for coupled heat and mass transfer in soil (Wilson *et al.* 1994). The FAO-56 dual crop coefficient method involves intensive computations for the estimation of E_s , but it requires fewer input parameters than the Shuttleworth–Wallace and the soil – atmosphere coupled models. In addition, since the FAO-56 model has been extensively applied to a wide range of situations, most of the required soil parameters can be found in past studies,

which makes it easier to adopt than the other models. Furthermore, the FAO-56 model has greater potential to accurately predict E_s under a range of soil surface wetting frequencies by irrigation and rainfall events, as it takes into account the wetted and exposed fractions of the soil surface from which most of the E_s generally occurs (Allen *et al.* 2005). Good E_s estimates were obtained in irrigated orchard crops such as olives and peaches using the FAO-56 dual crop coefficient method (Er-Raki *et al.* 2010; Paço *et al.* 2012). Unfortunately, most of the research conducted on pecan water use has only focused on quantification of total ET, making it difficult to partition between transpiration (T) and E_s (Miyamoto, 1983; Sammis *et al.* 2004; Wang *et al.* 2007; Samani *et al.* 2009; Samani *et al.* 2011), while very little information has been published on macadamia ET (Stephenson *et al.* 2003). This study will contribute to additional knowledge on the ET components of pecan and macadamia orchards, by providing accurate estimates of daily and seasonal E_s using the FAO-56 dual crop coefficient model, which takes into account variations in wetted and exposed fractions of the soil surface and the depth of the evaporation layer, as influenced by changes in types of irrigation systems, irrigation frequencies, canopy growth and soil types (Allen *et al.* 2005).

Thus, it was hypothesised that appropriate measurements of changes in canopy size, wetted fractions of the soil surface by irrigation and a detailed record of irrigation and rainfall events were required for accurate predictions of E_s in pecan and macadamia orchards using the FAO-56 dual crop coefficient method. Seasonal E_s was also predicted to be lower in mature orchards than in young orchards as a result of larger canopy cover in the former orchards, which would limit the occurrence of E_s even if irrigation wets a greater proportion of the orchard floor. The FAO-56 dual crop coefficient model was expected to be primarily sensitive to changes in canopy cover, fluctuations in wetted area and depth of the evaporation layer. Application of mulching materials on the wetted area by irrigation would considerably reduce E_s in open-canopy orchards. In order to test these hypotheses, the following objectives were formulated: (1) characterize E_s in pecan and macadamia orchards; (2) parameterize and validate the FAO-56 dual crop coefficient model for the estimation of daily E_s in these orchard crops; (3) conduct a sensitivity analysis to assess which model input parameters contribute most to output variability and (4) use the E_s model to assess different scenarios where orchard management strategies vary.

6.2 MATERIALS AND METHODS

6.2.1 Modelling of soil evaporation using the FAO-56 dual K_c approach

Estimation of E_s for pecan and macadamia orchards throughout the growing season was done for each experimental orchard using the FAO-56 dual crop coefficient approach, which was successfully parameterized and validated. Measurements of E_s conducted with micro-lysimeters in the 37-year-old pecan orchard, 7-year-old pecan orchard and 6-year-old macadamia orchard (methodology described in Chapter 3, Section 3.2.5) were used for model parameterization using three or four days of E_s measurements, while model validation was done using five to seven independent days of E_s measurements.

The modelling procedure consisted of determining the soil evaporation coefficient (K_e), which when multiplied by grass reference evapotranspiration (ET_0) provided soil evaporation estimates (E_s), as follows (Allen *et al.* 1998):

$$E_s = ET_0 K_e \quad (6.1)$$

Soil evaporation coefficient was estimated as follows (Allen *et al.* 1998):

$$K_e = K_r (K_{c \max} - K_{cb}) \leq f_{ew} K_{c \max} \quad (6.2)$$

where K_{cb} is the basal crop coefficient, which in this study was assumed to be equal to the transpiration crop coefficient (K_t) determined from T measurements at the study sites, assuming that when the soil surface is dry, the amount of soil water evaporated is negligible; $K_{c \max}$ is the maximum value of the crop coefficient following rain or irrigation, K_r is a dimensionless evaporation reduction coefficient, which is dependent on the cumulative depth of water depleted (evaporated) from the soil surface and f_{ew} is the fraction of the soil that is both exposed to solar radiation (or not shaded by the tree canopy) and wetted.

The value of $K_{c \max}$ was set at 1.4 for pecans and 1.0 for macadamias, based on the maximum values for K_t of 1.35 observed in the mature pecan orchard at Cullinan and

0.95 in the young macadamia orchard at White River, plus 0.05 (an empirical coefficient which accounts for the increase in the value of K_t when the soil is wet following complete wetting of the soil surface, even during periods of full ground cover, Allen *et al.* 2005).

Soil evaporation reduction during a complete drying cycle was estimated as follows (Allen *et al.* 1998):

$$TEW = (\theta_{FC} - 0.5\theta_{PWP})Z_e \quad (6.3)$$

where TEW is total evaporable water in mm, θ_{FC} is volumetric soil water content at field capacity, θ_{PWP} is volumetric soil water content at wilting point and Z_e is an arbitrary parameter representing the thickness of the top soil layer. The soil evaporation modelling procedure assumes that the water content of the evaporating layer of the soil is at θ_{FC} , shortly following a major wetting event and that the soil can dry to a soil water content level that is halfway between oven dry (no water left) and wilting point, θ_{PWP} . Allen *et al.* (1998) recommends selection of appropriate Z_e values that represent the values of E_s observed over complete drying cycles via model calibration using E_s measurements. For this study, values of Z_e were fixed at 50 mm for a sandy soil, 70 mm for a sandy loam soil and 90 mm for a sandy clay loam soil. Soil water content at field capacity ($0.165 \text{ m}^3 \text{ m}^{-3}$ for a sandy soil, $0.224 \text{ m}^3 \text{ m}^{-3}$ for a sandy loam soil and $0.260 \text{ m}^3 \text{ m}^{-3}$ for a sandy clay loam soil) and permanent wilting point ($0.09 \text{ m}^3 \text{ m}^{-3}$ for all soil types in this study) were calculated using the approach described by Saxton *et al.* (1986), which takes into account soil texture characteristics of the top layer at the study sites (80% sand, 6% silt and 7% clay for Cullinan; 72% sand, 5% silt and 18% clay for White River and 67% sand, 9% silt and 24% clay for Hatfield).

The value of TEW was subsequently used to compute the soil evaporation reduction cycle, following the procedure described by Allen *et al.* (1998), which runs through two different stages: (1) stage 1, which is an energy limiting stage and (2) stage 2, which is a falling rate stage. Stage 1 occurs at the start of a drying cycle, following heavy rain or irrigation and, therefore, the soil water content in the topsoil is assumed to be at field capacity. During stage 1, the soil surface remains wet and it is assumed that evaporation from soil exposed to the atmosphere will occur at the maximum rate ($K_r =$

1), limited only by energy availability at the soil surface. The cumulative depth of evaporation, D_e , at the end of stage 1 is the maximum depth of water that can be evaporated from the topsoil layer without restriction, termed readily evaporable water (REW), which was taken as 6 mm for a sandy soil, 8 mm for a sandy loam soil and 10 mm for a sandy clay loam soil (Allen *et al.* 1998). As the topsoil layer dries out, stage 2 begins during which less water is available for evaporation, and consequently, a reduction in E_s occurs in proportion to the amount of water remaining in the topsoil layer (Allen *et al.* 1998):

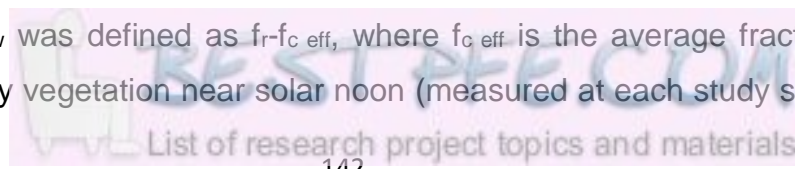
$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \quad \text{for } D_{e,i-1} > REW \quad (6.4)$$

where $D_{e,i-1}$ is the cumulative depth of evaporation (depletion) from the topsoil layer at the end of day $i-1$ (the previous day) in mm, which is calculated through a daily water balance computation for the surface soil layer, as described by Allen *et al.* (1998):

$$D_{e,i-1} = D_{e,i} + (P_i - RO_i) + \frac{I_i}{f_w} - \frac{E_{s,i}}{f_{ew}} - T_{ew,i} - DP_{e,i} \quad (6.5)$$

where , $D_{e,i}$ is the cumulative depth of evaporation (depletion) following complete wetting at the end of day i (mm), P_i precipitation on day i (mm), RO_i precipitation runoff from the soil surface on day i (mm), I_i irrigation depth on day i that infiltrates the soil (mm), $E_{s,i}$ evaporation on day i (i.e., $E_{s,i} = K_e ET_o$) (mm), $T_{ew,i}$ depth of transpiration from the exposed and wetted fraction of the soil surface layer on day i (mm), $DP_{e,i}$ deep percolation loss from the topsoil layer on day i if soil water content exceeds field capacity (mm), f_w fraction of soil surface wetted by irrigation (0.01 – 1), f_{ew} exposed and wetted soil fraction (0.01 – 1). The parameter RO_i was assumed to be zero, since almost all precipitation events that had intensities or depths large enough to cause runoff were likely to replenish the water content of the topsoil layer to field capacity. The value of $T_{ew,i}$ was also considered negligible, as according to Allen *et al.* (1998) the amount of transpiration from the evaporating soil layer is very small that can be ignored.

The parameter f_{ew} was defined as $f_r - f_{c\text{ eff}}$, where $f_{c\text{ eff}}$ is the average fraction of soil surface covered by vegetation near solar noon (measured at each study site using a



ceptometer and/or a grid method to determine the ground shaded area) and f_r is the fraction of soil surface wetted by irrigation and/or rainfall, which is taken as 1.0 according to Allen *et al.* (1998) and Allen *et al.* (2005), regardless of the type of ground cover. However, measurements of E_s with micro-lysimeters, conducted in the young pecan orchard at Hatfield, in which 60% of the ground surface in-between tree rows was covered by short grass and grass residues, showed much lower E_s rates on the area covered by the short grass (0.32 to 0.80 mm day⁻¹), as compared to the area with bare soil (2.4 to 3.5 mm day⁻¹) following a rainfall event. As a result, there was a need to include an adjustment factor to account for lower E_s rates on soils with exposed ground area partially covered with short grass and grass residues. Under such conditions, Allen *et al.* (2005) suggests reducing the value for TEW to account for this decrease in E_s , but in this study a better adjustment was made by fixing the parameter f_r at 0.42 through model calibration for the young pecan orchard at Hatfield, while standard f_r values of 1.0 were used in the mature pecan orchard with a bare soil and young macadamia orchard, with 25% of the ground surface covered with actively growing grass. Rosa *et al.* (2012a) suggested a similar approach for the adjustment of f_r fraction used in computing K_e in the presence of a ground cover which contributes to reduced E_s . This is probably an acceptable suggestion, as the live vegetation cover is usually cutback frequently, with vegetation residues left on the soil surface as mulch.

Since only a fraction of the ground surface is wetted after an irrigation event, f_{ew} was limited to f_w during those days (the fraction of the soil surface wetted by irrigation). Both f_{ew} and f_w are taken as the minimum between the fraction of soil surface that is exposed to incident solar radiation and the fraction of soil surface that is wetted by either irrigation and/or rainfall and irrigation only, calculated as follows:

$$f_{ew} = \min(1 - f_{c\text{ eff}}, 1) \quad (6.6)$$

$$f_w = \min(1 - f_{c\text{ eff}}, f_w) \quad (6.7)$$

The amount of water in the f_{ew} and f_w fractions of the soil surface is assumed to be available solely for E_s in deep-rooted perennial tree crops, as the amount of water extracted for transpiration in this layer is generally small and can be ignored (Allen *et al.* 2005). The upper limit of K_c is subsequently computed as $f_{ew} K_{c\text{ max}}$ or $f_w K_{c\text{ max}}$ (Allen

et al. 1998). The resultant value is then compared against the soil evaporation coefficient to ensure that it is less than the upper limit (Equation 6.2). Table 6.1 shows values for the different soil and crop parameters that were used for model parameterization.

Table 6.1 Soil and crop parameters used for parameterization of the FAO-56 dual crop coefficient model to estimate soil evaporation in the different experimental orchards.

Parameters	Experimental orchard		
	37-year-old pecan	7-year-old pecan	6-year-old macadamia
Depth of the soil surface layer (m)	0.05	0.09	0.07
θ at FC ($\text{m}^3 \text{m}^{-3}$)	0.165	0.260	0.224
θ at PWP ($\text{m}^3 \text{m}^{-3}$)	0.09	0.09	0.09
Soil surface area wetted by irrigation (m^2)	39.0	12.5 – 25.0	18.0
Fraction of soil surface wetted by irrigation	0.56	0.25	0.56
K_c max	1.4	1.4	1.0
Fraction of soil surface covered by the tree canopy	0.51 – 0.98	0.09 – 0.18	0.35 – 0.75

6.2.2 Sensitivity analyses of daily soil evaporation modelling input parameters

The FAO-56 dual crop coefficient approach for estimation of daily E_s in orchard crops was evaluated for its sensitivity to a marginal change in the main input parameters, namely (Table 6.2): (1) maximum value of crop coefficient ($K_{c \text{ max}}$), determined for pecans and macadamias based on field measurements; (2) thickness of the top soil layer (Z_e) fixed for each soil type through model parameterization; (3) fraction of the soil surface wetted by irrigation (f_w) measured for each irrigation system at each study orchard and (4) effective fractional canopy cover ($f_{c \text{ eff}}$), measured using a ceptometer and/or estimated with a grid method. The procedure ran similarly to that described for sensitivity analyses of daily transpiration modelling input parameters (Section 5.2.3), which consisted of evaluating the estimated output percentage difference when varying each input parameter $\pm 20\%$ of actual input value using the sensitivity index (SI) method as described by Hamby (1994).

Table 6.2 Input parameters selected for sensitivity analyses in the FAO-56 dual crop coefficient approach to model daily soil evaporation.

Model	Model parameter	37-year-old pecans		7-year-old pecans		6-year-old macadamias	
		Min	Max	Min	Max	Min	Max
FAO-56 dual crop coefficient	Maximum value of crop coefficient ($K_{c\ max}$)	1.1	1.4	1.1	1.4	0.8	1.0
	Thickness of the top soil layer (Z_e - m)	0.04	0.06	0.07	0.11	0.06	0.08
	Fraction of the soil surface wetted by irrigation (f_w)	0.45	0.67	0.2	0.3	0.45	0.67
	Effective fractional canopy cover ($f_{c\ eff}$)	0.41	0.98	0.07	0.20	0.28	0.90

6.2.2 Soil evaporation modelling scenarios

Mechanistic E_s simulation models can be relevant tools for evaluating possible orchard management options to reduce or suppress E_s in order to improve crop water use efficiency without compromising T of the crop. With such intention, the FAO-56 dual K_c model was used to estimate seasonal E_s under varying conditions of orchard management, namely 50% of the surface area wetted by irrigation covered with mulch, as compared to the actual management practice by the grower of maintaining the wetted surface area by irrigation uncovered (Table 6.3).

Table 6.3 Description of orchard characteristics and soil evaporation modelling scenarios simulated.

Orchard Type	Configuration	Fraction of canopy cover	Orchard management	Actual practice	Modelling scenario
Young pecans	Rectangular	0.09 - 0.18	Irrigation frequency	Once per week	Once per week
			Irrigation type	Drip	Drip
			Ground cover in between tree rows	Grass	Grass
			Ground cover in the wetted area by irrigation	Bare ground	50% covered with mulch
Mature pecans	Triangular	0.51 - 0.82	Irrigation frequency	Once per week	Once per week
			Irrigation type	Micro-sprinkler	Micro-sprinkler
			Ground cover in between tree rows	Bare ground	Bare ground
			Ground cover in the wetted area by irrigation	Bare ground	50% covered with mulch
Young macadamias	Hedgerow	0.35 - 0.67	Irrigation frequency	Everyday	Everyday
			Irrigation type	Drip	Drip
			Ground cover in between tree rows	Grass	Grass
			Ground cover in the wetted area by irrigation	Bare ground	50% covered with mulch

6.3 RESULTS AND DISCUSSION

6.3.1 Spatial and temporal variability of measured soil evaporation

6.3.1.1 *Spatial variation of daily soil evaporation within and outside the irrigated area*

Measurements of daily E_s were conducted in different orchards and locations, namely a 37-year-old pecan orchard at Cullinan, a 6-year-old macadamia orchard at White River and a 7-year-old pecan orchard at Hatfield, in order to assess spatial variability of E_s as affected by differences in climatic conditions, irrigation strategies, soil types, orchard configuration and ground and canopy cover. Figure 6.1 illustrates spatial variability of E_s in the 37-year-old micro-sprinkler irrigated pecan orchard as influenced by spatial variations of volumetric soil water content (θ) around the area allocated to one tree. Distances (1.5, 3.0 and 4.5 m) away from the tree, within the tree row, represent the irrigated area on the side of the emitter, while negative values represent the area opposite to the emitter. Distances (1.5, 3.0 and 4.5 m) away from the tree, across the row, represent the area on the side of the road where the trees had been pruned, while negative values represent the area on the side of the road where the trees had not been pruned.

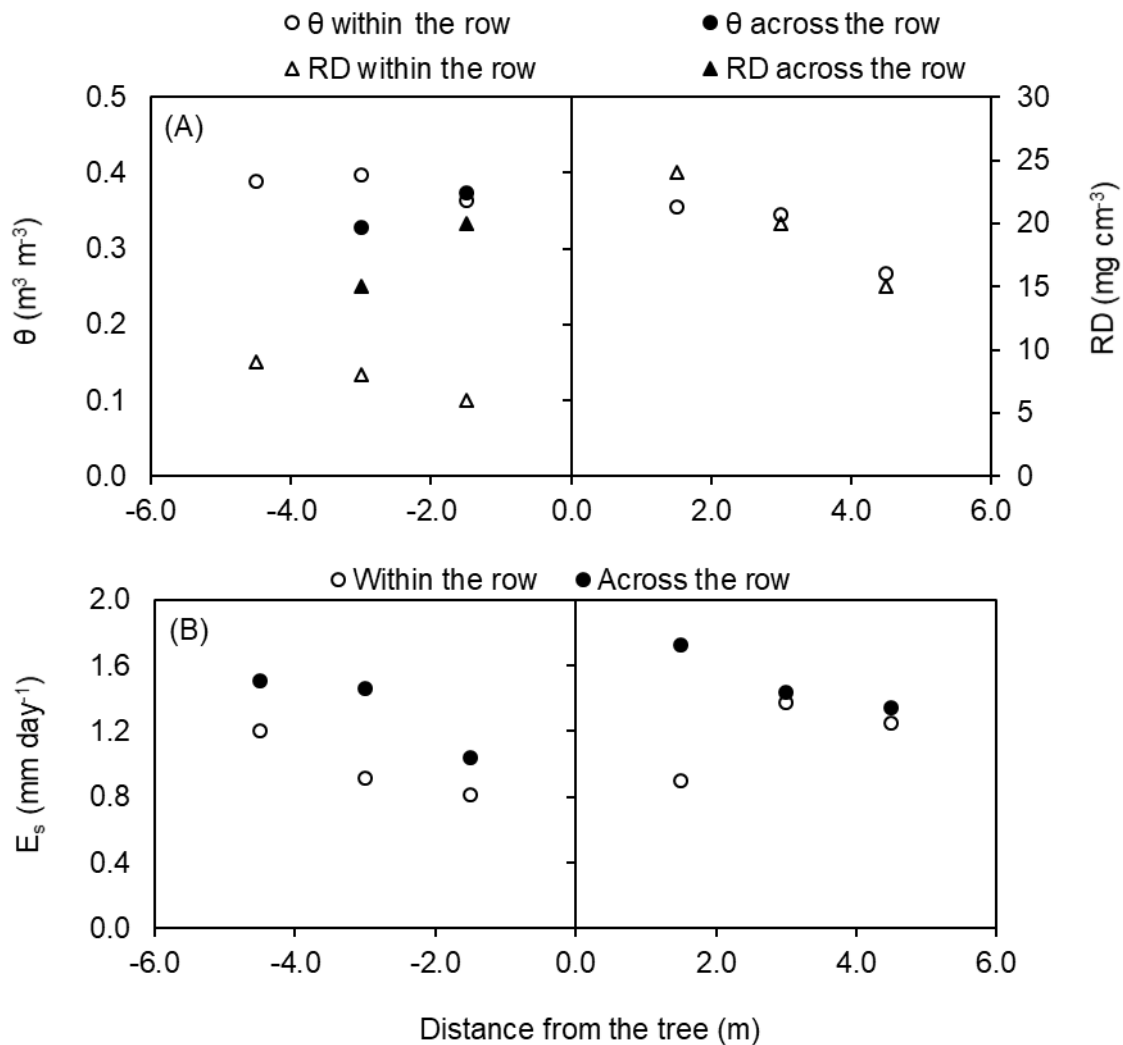


Figure 6.1 Daily average (A) volumetric soil water content (θ) in the top surface layer (0 – 15 cm) and rooting density (RD) and (B) soil evaporation (E_s) at various positions away from a 37-year-old micro-sprinkler irrigated pecan tree, measured for 10 days during February and March 2012 at the Cullinan experimental site.

From Figure 6.1, it is clear that in this closed-canopy, micro-sprinkler irrigated pecan orchard, spatial variation of θ is not the only dominant factor controlling E_s . Values of θ were fairly high ($0.39 \text{ m}^3 \text{ m}^{-3}$) within 3.0 m of the tree along the row and within 1.5 m from the tree across the row, but E_s was quite variable (fluctuating between 0.8 and 1.5 mm day^{-1}). This probably reflects the spatial variability in incident solar radiation, as measurements of transmitted solar radiation conducted beneath the canopy at the study site using solarimeters generally showed low values close to the tree trunk due

to shading by the canopy, whilst at 3.0 to 4.5 m away from the trunk more solar radiation reached the soil surface. A clear example of a possible influence of incident solar radiation on E_s can be observed in areas opposite to the emitter within the row and on the side of the road where the trees had not been pruned, where E_s increased moving further away from the trunk (Figure 6.1B). Surprisingly, θ was quite high in areas opposite to the emitter (Figure 6.1A), despite little irrigation water supply, which is likely to be due to lower rainfall interception by the canopy or due to the influence of water supply and distribution from the micro-sprinkler at the next tree in the row.

Spatial variability of E_s was less complex in the open-canopy, drip irrigated pecan orchard, as observed in Figure 6.2. Distances (5.0 and -5.0 m) away from the tree within the row represent the area around the tree with bare soil, under a dripper and exposed to solar radiation, whilst positioning across the row (positive values on one side and negative values on the other side of the tree, at 0.35 and 5.0 m away) represent the areas under a dripper and a 6.0 m wide grass strip. The distance at 0.0 m represents the area next to the tree trunk, under the central dripper line and in between two lateral dripper lines.

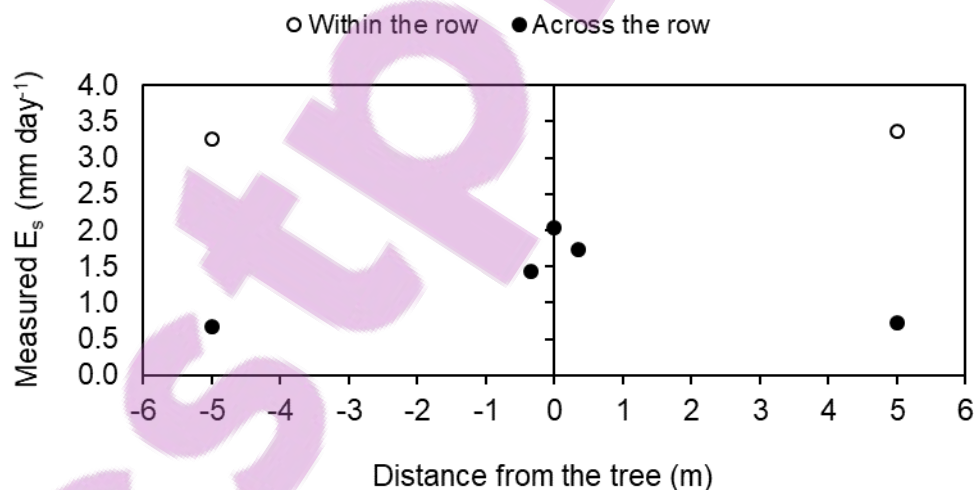


Figure 6.2 Daily average soil evaporation (E_s) at various positions away from a 7-year-old drip irrigated pecan tree, measured for seven days during April 2013 at the Hatfield experimental site.

As evident in Figure 6.2, daily E_s was highest (2.8 mm day^{-1}) at 5.0 m away from the trunk within the row, which was wet bare soil, exposed to solar radiation, and was lowest (0.5 to 0.6 mm day^{-1}) at 5.0 m away from the trunk across the row, which received no irrigation (only rainfall = 22 mm) and was covered by a short-grass and grass residues. In this case, grass residues left on the soil surface after grass mowing acted as mulch, shading the soil surface from the sun, resulting in limited E_s as observed by Tolk *et al.* (1999) on maize cropped fields. Intermediate values of daily E_s (1.1 to 1.7 mm day^{-1}) occurred in the wetted area close to the tree trunk, where E_s was limited by the available energy reaching the soil surface due to shading by the tree canopy.

Maximum daily E_s rates were higher at specific positions around a 7-year-old pecan tree (2.8 mm day^{-1}) than around a 37-year-old tree (1.7 mm day^{-1}), but daily weighted average E_s rates were similar in these two distinct orchards (varying between 1.19 and 1.28 mm day^{-1}). This is expected, as in both orchards there were factors limiting maximum E_s rates. The 37-year-old orchard had high canopy cover for the majority of the growing season, with maximum values varying between 0.82 and 0.98 thus limiting the amount of energy available for E_s , while the 7-year-old orchard was drip irrigated, with a smaller wetted area and 60% of the ground covered with short-grass and grass residues which restricted the area with available water supply for E_s .

Spatial variation of E_s in the young, drip irrigated macadamia orchard, planted in hedge-rows, is illustrated in Figure 6.3. Soil evaporation was highly variable at different positions across the tree row (namely on the road area covered by grass (G), furrow (F), ridge (R) and under the dripper (UD), on both sides of the tree row, west (W) and east (E), as well as in the centre of the tree row in between the drippers (ID)), with the dominant factors controlling E_s changing throughout the growing season. Although θ was the highest in the G area, E_s in this area was only high during summer and autumn periods, probably due to increased θ and the presence of an active ground cover. In winter, on the other hand, E_s in the G area was the lowest due to reduced θ , and the highest in the wetted area (UD-W, ID and UD-E) due to a smaller canopy at this time. Surprisingly, E_s from the wetted area during summer and autumn was not noticeably higher than the E_s from the rest of the orchard (G-W, F-W, R-W, G-E, F-E and R-E),

due to higher canopy growth during these periods, which limited solar radiation incident on the ground. The increased amount of roots in areas UD (35 mg cm^{-3}) and ID (30 mg cm^{-3}) probably contributed to lower levels of θ as compared to the G area (20 mg cm^{-3}), but this had little influence on spatial distribution of E_s .

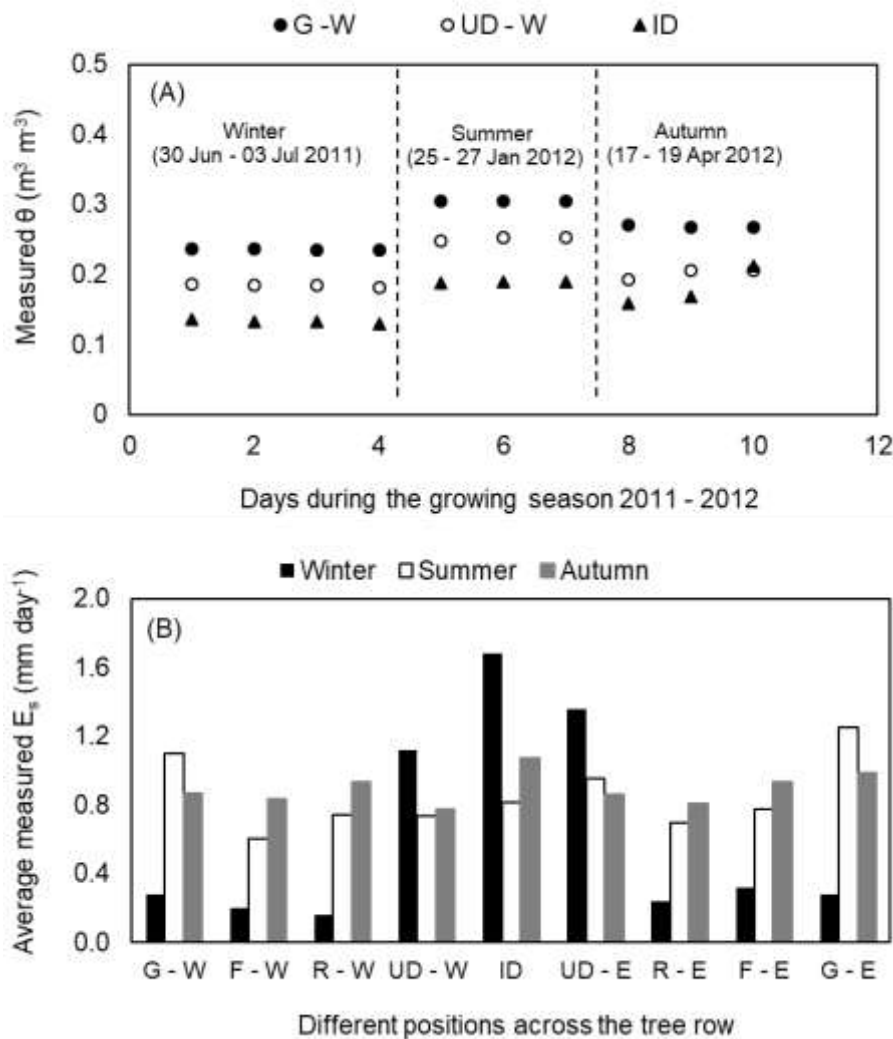


Figure 6.3 Changes in (A) volumetric soil water content (θ) in the top surface layer (0 – 15 cm) and (B) average daily soil evaporation (E_s) at various positions across the row (on the road area covered by grass - G, furrow - F, ridge - R and under the dripper - UD, on both sides of the tree row, west - W and east - E, as well as in the centre of the tree row in between the drippers - ID) of a 6-year-old drip irrigated macadamia orchard, for three to four days during winter, summer and autumn measurement periods in the 2011/2012 growing season at the White River experimental site.

Thus, a number of factors played an important role in controlling the spatial distribution of E_s in pecan and macadamia orchards, with the most dominant factors including canopy size, soil water content and the type of ground cover, as pointed out by Wang and Liu (2007) for E_s under the canopy of annual crops. Results from this study suggest that both supply and demand limiting conditions restrict maximum E_s rates (with the former being more important in young orchards and the latter in mature orchards). Canopy size played a more significant role in controlling E_s in pecan orchards (deciduous species) compared to the macadamia orchard (evergreen species), which is probably due to differences in canopy architecture, intensity and type of pruning and planting configurations. The least important factor playing a role on E_s variability was found to be root density in these orchards of tree nut crops, which supports the statement by Allen *et al.* (2005) that water extraction by roots of perennial crops in the soil surface layer is generally small and a decrease in soil water content caused by transpiration of the crop can be ignored, as a result E_s becomes unaffected by crop transpiration.

6.3.1.2 Temporal variability of soil evaporation

Temporal variability in atmospheric variables and θ as influenced by rainfall and irrigation events also affected changes in E_s . Figure 6.4 illustrates a typical example of daytime fluctuations of E_s as affected by changes in atmospheric evaporative demand (ET_o) and θ of the top surface layer in the mature pecan orchard.

Daytime changes in E_s responded to ET_o , regardless the amount of θ in the first 0 – 15 cm soil layer (Figure 6.4). Values of E_s were maximum at midday (0.16 to 0.19 mm hr⁻¹) and minimum in the beginning and end of the day (typically varying from 0.01 to 0.04 mm hr⁻¹). Soil water content (θ) did not limit E_s during this measurement period, as it followed three consecutive daily rainfall events, summing a total of 19 mm of rainfall. As described by Allen *et al.* (1998), following heavy rain or irrigation, θ in the topsoil is at field capacity and, as a result, E_s from soil exposed to the atmosphere will occur at the maximum rate, limited only by the energy availability at the soil surface. Daytime fluctuations of E_s were linearly correlated to changes in solar radiation (R_s),

demonstrating that this is the most dominant atmospheric variable controlling E_s when water is not limiting (Figure 6.5). Of all the different climatic variables, solar radiation is the factor that relates the most to changes in the atmospheric evaporative demand (represented by ET_o), which in combination with a soil evaporation coefficient is often used to predict E_s of cropped fields (Allen *et al.* 1998; Allen, 2000; Allen *et al.* 2005; Er-Raki *et al.* 2007; Er-Raki *et al.* 2008; Er-Raki *et al.* 2010; Li *et al.* 2010; Liu and Luo, 2010; Rosa *et al.* 2012b; Pereira *et al.* 2015).

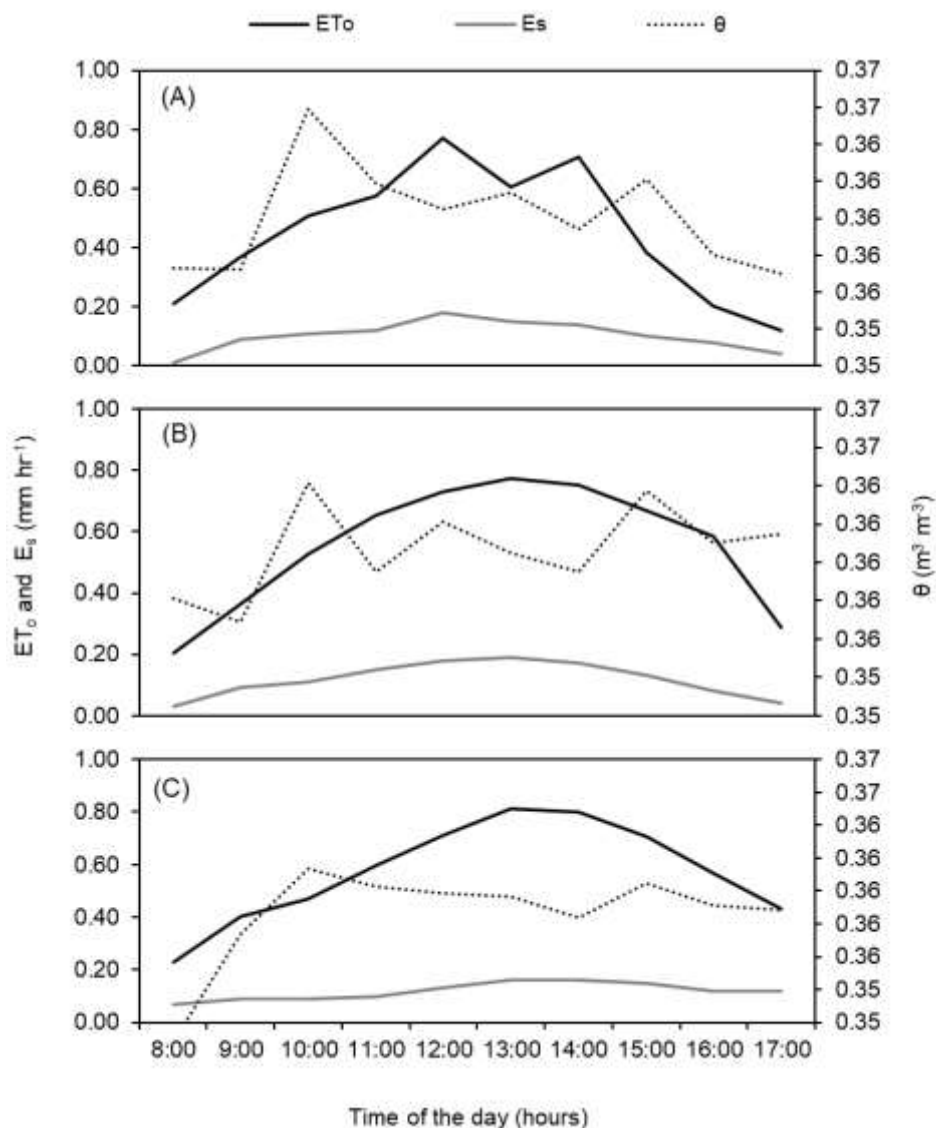


Figure 6.4 Daytime changes in soil evaporation (E_s) as influenced by hourly fluctuations in atmospheric evaporative demand (ET_o) and volumetric soil water content (θ) of the top surface layer, on typical sunny days between 21 and 23 February 2012 (A to C, respectively), in the 37-year-old pecan orchard at Cullinan.

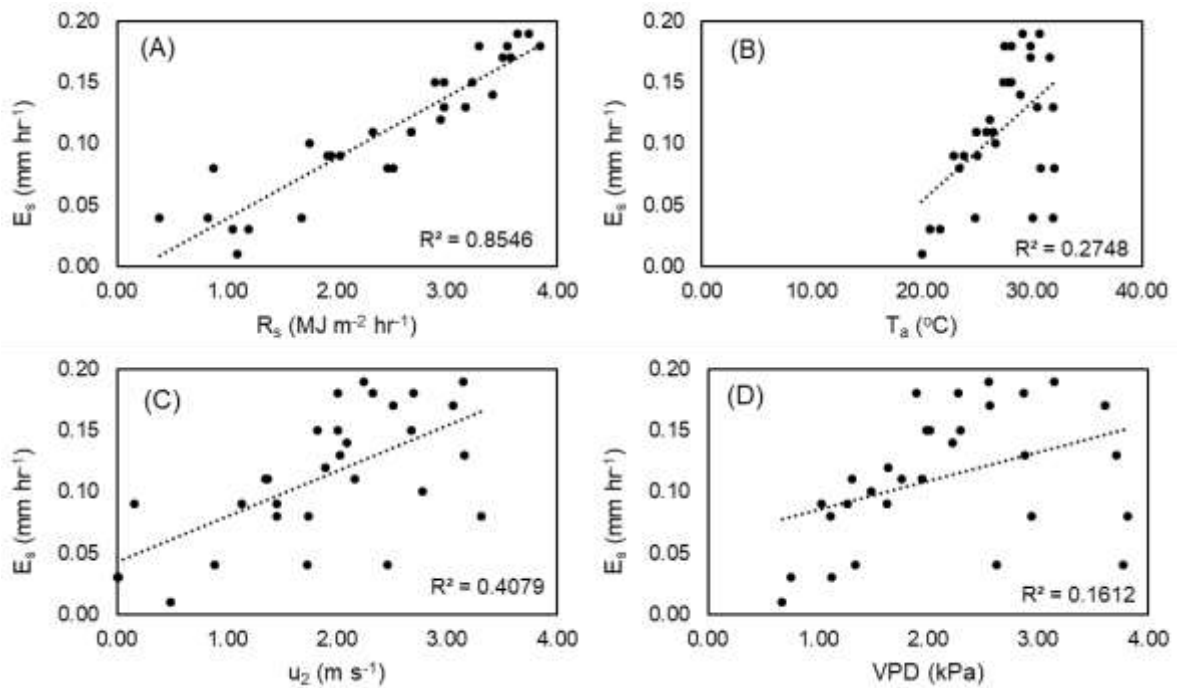


Figure 6.5 Linear dependency of daytime fluctuations of soil evaporation (E_s) on different atmospheric variables, namely (A) solar radiation - R_s , (B) mean air temperature - T_a , (C) wind speed – u_2 and (D) vapour pressure deficit - VPD in the 37-year-old pecan orchard at Cullinan.

When water is a limiting factor, E_s from the exposed soil is likely to decrease in proportion to the amount of water remaining in the surface soil layer. Figure 6.6 illustrates changes in E_s for five successive days following an irrigation event of 32 mm in the mature pecan orchard at the Cullinan experimental site. Soon after the irrigation (25 – 26 February 2012), E_s occurred at the maximum rate as dictated by the energy available at the soil surface (stage 1 or energy limited stage). In the following days (27 – 29 February 2012), as the soil surface layer dried out E_s was likely to progress at limited rates below the potential evaporation rates (stage 2, termed falling rate stage).

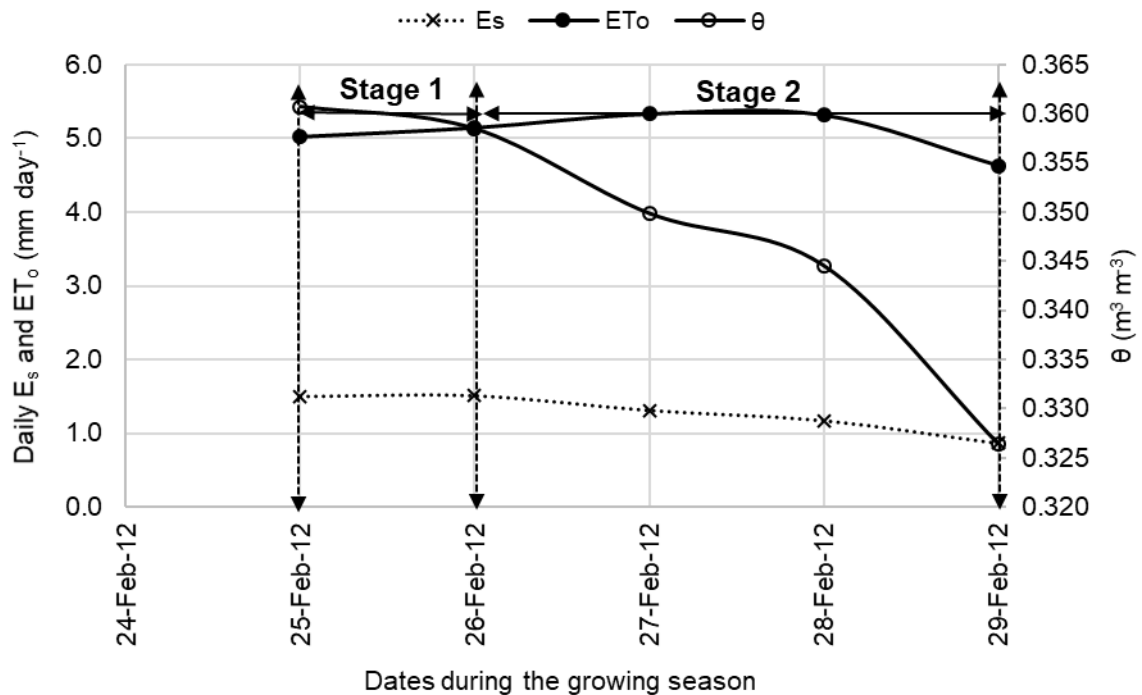


Figure 6.6 Changes in soil evaporation (E_s) for five consecutive days following an irrigation event of 32 mm in the mature pecan orchard at the Cullinan site, as influenced by fluctuations in reference evapotranspiration (ET_0) and volumetric water content (θ) of the first 0 – 15 cm soil layer. The two stages of E_s are also illustrated, whereby E_s proceeds at maximum rates when θ is not limiting (stage 1 – energy limiting stage), followed by E_s limited by the availability of water in the top soil layer (stage 2 - falling rate stage).

Understanding the spatial and temporal variability of E_s in pecan and macadamia orchards helps with the selection of an appropriate modelling approach to estimate daily changes of E_s in these orchards. Field measurement results revealed that several factors play a role in controlling E_s , including changes in canopy size, weather conditions, soil water content of the surface layer and the frequency of irrigation and rainfall events. Thus, for accurate predictions of daily changes in E_s , the selected modelling approach should take into account all these aspects. The next section presents and discusses results of parameterization and validation of a mechanistic E_s modelling approach, as well as its applicability for estimating daily changes in E_s , which will significantly contribute to more accurate quantification of daily ET for improved irrigation scheduling of these orchard crops.

6.3.2 Parameterization and validation of the FAO-56 dual K_c model

The FAO-56 dual K_c model was parameterized and validated using independent data sets of daily measured values of E_s collected for 10 to 14 days at each experimental site. The soil texture of the surface layer (top 0 – 10 cm) varied for each orchard: sandy in the mature pecan orchard at Cullinan, sandy clay loam in the young pecan orchard at Hatfield and sandy loam in the macadamia orchard at White River. The FAO-56 model was successfully parameterized (with coefficient of determination – R^2 varying from 0.82 to 0.98 and mean absolute percent difference – MAPD from 4 to 14%) and validated (R^2 from 0.64 to 0.86 and MAPD from 7 to 17%) for each soil type (Figure 6.7).

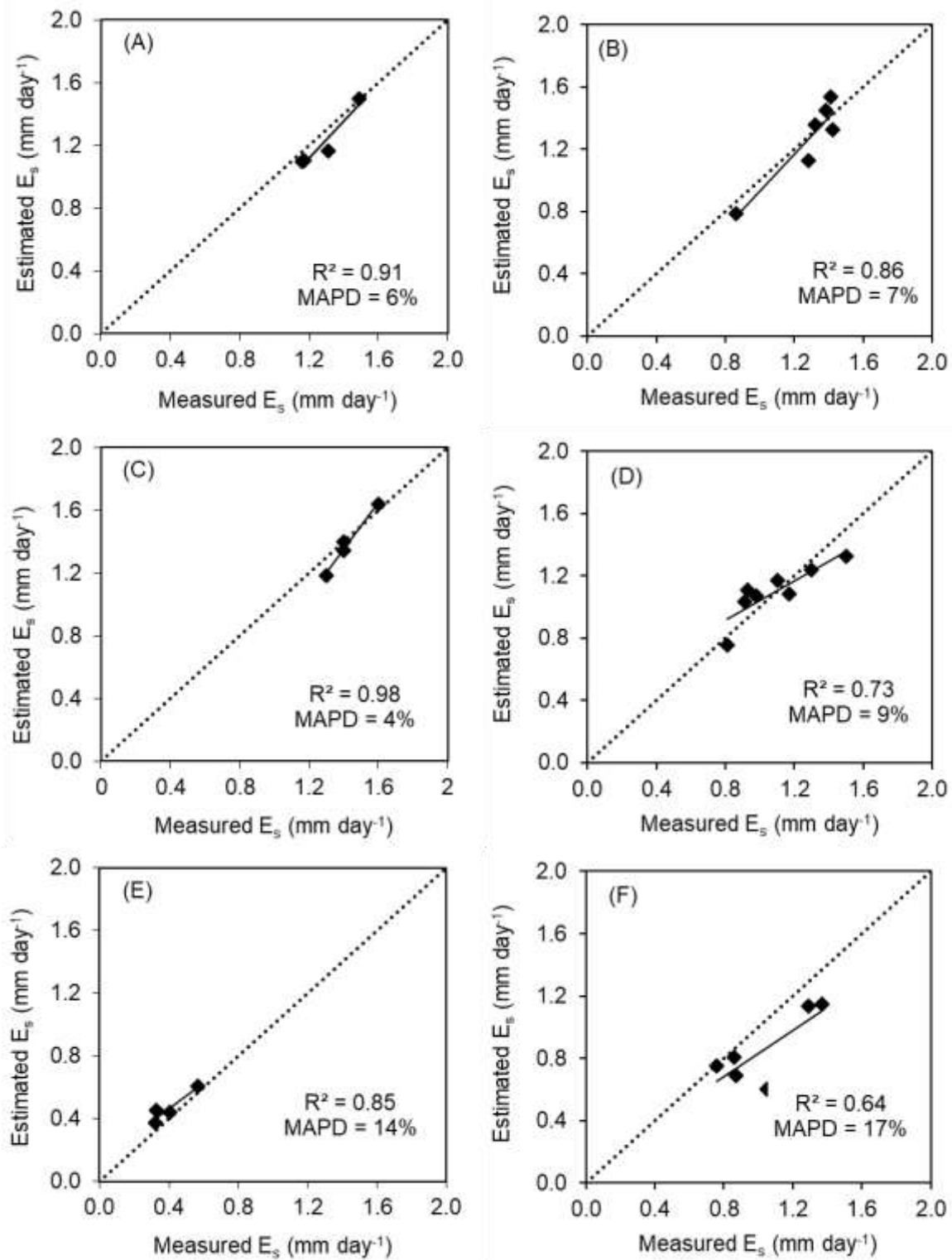


Figure 6.7 FAO-56 dual K_c model for a sandy soil in the mature pecan orchard (parameterization – A; validation – B), sandy clay loam soil for the young pecan orchard (parameterization – C; validation – D) and sandy loam soil for the macadamia orchard (parameterization – E; validation – F).

The FAO-56 dual K_c model was better parameterized and validated for the pecan orchards (Figure 6.7A, B, C and D) than for the macadamia orchard (Figure 6.7E and F). This is likely due to the fact that both the pecan orchards were irrigated less frequently (typically once per week) than the macadamia orchard (with irrigation occurring three to five times per day and one to two hours per event, increasing from winter to summer, almost every day excluding rainy days). Thus, the low frequency of irrigation events in pecan orchards allowed more accurate measurements of E_s using micro-lysimeters as compared to the high frequency irrigation events. As pointed out by Daamen *et al.* (1993), errors may occur during E_s measurements using micro-lysimeters if the soil within the micro-lysimeter has a significantly different water content to that of the surrounding soil, which may be caused by the presence of a boundary to water flow imposed at the base of the micro-lysimeter at the time of soil core extraction. This is the reason why these authors recommended that extraction of soil cores should be done two or more days after rainfall or irrigation events, which was not possible in the drip irrigated macadamia orchard due to high frequency irrigation intervals. In addition, it is impossible to measure E_s with micro-lysimeters during irrigation events, and as a result, daily E_s measurements may be underestimated, with errors increasing as the irrigation frequency also increases. High frequency irrigation in the macadamia orchard also limited E_s measurements during the falling rate stage, where E_s progresses below the potential evaporation rates, limited by the remaining available soil water at the surface layer. Despite these limitations, acceptable results were obtained in this orchard for model parameterization and validation.

6.3.3 Sensitivity analyses of the different model input parameters

Results of a sensitivity analysis of the main input parameters affecting E_s predictions using the FAO-56 dual K_c model is presented in Table 6.4.

Table 6.4 Sensitivity analysis results on seasonal soil evaporation predicted using the FAO-56 dual K_c model.

Model parameters	Sensitivity index (SI, %)		
	37-year-old pecan	7-year-old pecan	6-year-old macadamia
$K_{c\ max}$	6	18	21
Z_e	12	7	0
f_w	0	12	26
$f_{c\ eff}$	59	16	14

Results presented in Table 6.4 indicate that sensitivity of E_s to the estimation of $K_{c\ max}$ and f_w values is higher in young orchards (SI = 18 – 21% and 12 – 26%, respectively) as compared to the mature orchard (SI = 6% and 0%, respectively). The opposite is true for $f_{c\ eff}$, where the E_s estimates were more sensitive to changes in $f_{c\ eff}$ for the mature orchard (SI = 56%) than for young orchards (SI = 12 to 26%). This demonstrates that, in mature, closed-canopy orchards the most limiting factor for E_s is the fraction of soil exposed to solar radiation, while in young, open-canopy orchards E_s is mainly limited by the fraction of soil surface exposed and wetted by irrigation. The high energy available for E_s at the soil surface of young orchards causes higher sensitivity of E_s estimates to the parameter $K_{c\ max}$ in these orchards compared to the mature orchard. The sensitivity of the parameter Z_e , on the other hand, was influenced by the frequency of irrigation intervals (higher SI values were found for pecan orchards in which irrigation took place typically once per week, contrary to macadamias which were irrigated almost every day, with multiple events per day). This contributed to fairly high soil water content levels in the topsoil layer for the macadamia orchard (close to field capacity), which resulted in maximum soil evaporation reduction coefficients ($K_r = 1$) almost for the entire growing season. Under such conditions, evaporation from soil exposed to the atmosphere is likely to occur at a rate limited by the energy availability at the soil surface (stage 1 of E_s), and as a result, changes in Z_e will have little influence on E_s . This shows that model calibration to determine the parameter Z_e is very crucial in orchards which are irrigated less frequently, and negligible otherwise. Results from the sensitivity analysis conducted are supported by the findings obtained by Allen *et al.* (2005), who investigated the sensitivity of the FAO-56 dual K_c model for the estimation of ET of annual crops. These authors found negligible impact of changes in $f_{c\ eff}$ during initial and development growth stages on E_s , when the fraction

of the soil surface exposed to solar radiation exceeded the fraction of soil surface wetted by irrigation. This study further illustrated that the sensitivity response of the different model input parameters varied across a range of conditions, being mostly affected by the canopy size and fraction of the soil surface wetted by irrigation. Thus, in closed-canopy orchards it is important that good measurements of $f_{c\text{ eff}}$ are made, while in open-canopy orchards adequate measurements of f_w should be conducted in order to obtain accurate estimates of E_s using the FAO-56 dual K_c model.

6.3.4 Estimation of soil evaporation throughout the entire experimental period

The FAO-56 dual K_c model, which was successfully calibrated and validated with field measurements of E_s at each experimental site, was used to estimate daily E_s for the entire experimental period, between 2009 - 2012 in the micro-sprinkler irrigated, mature pecan orchard at Cullinan, 2012 - 2013 in the drip irrigated, young pecan orchard at Hatfield and 2010 - 2012 in the drip irrigated, young macadamia orchard at White River. Figure 6.8 illustrates daily changes in E_s during three consecutive seasons of measurements at Cullinan, as affected by rainfall and irrigation events, as well as by the daily fluctuations in atmospheric evaporative demand. In all three seasons the highest daily E_s rates occurred at the beginning of the season, during October and November (maximum values varying between 2.6 and 3.4 mm day⁻¹), when the canopy was coming into leaf, $f_{c\text{ eff}}$ was low (60 to 80%), and atmospheric evaporative demand was high (maximum values between 6 and 8 mm day⁻¹). The canopy size of this mature pecan orchard reached maximum values between 82 and 98%, which considerably limited E_s , particularly in the first two seasons of measurements (Figure 6.8A and B). Reduced E_s rates were also evident towards the end of the season (May), when negligible rainfall and irrigation occurred and ET_o was much lower (1 to 3 mm day⁻¹). Total seasonal E_s was the highest (180 to 192 mm) during the 2009/2010 and 2011/2012 growing seasons as a result of lower $f_{c\text{ eff}}$ for the majority of the growing period due to more intensive pruning practices, and lowest in the 2010/2011 season (71 mm), due to earlier canopy closure and higher canopy cover.

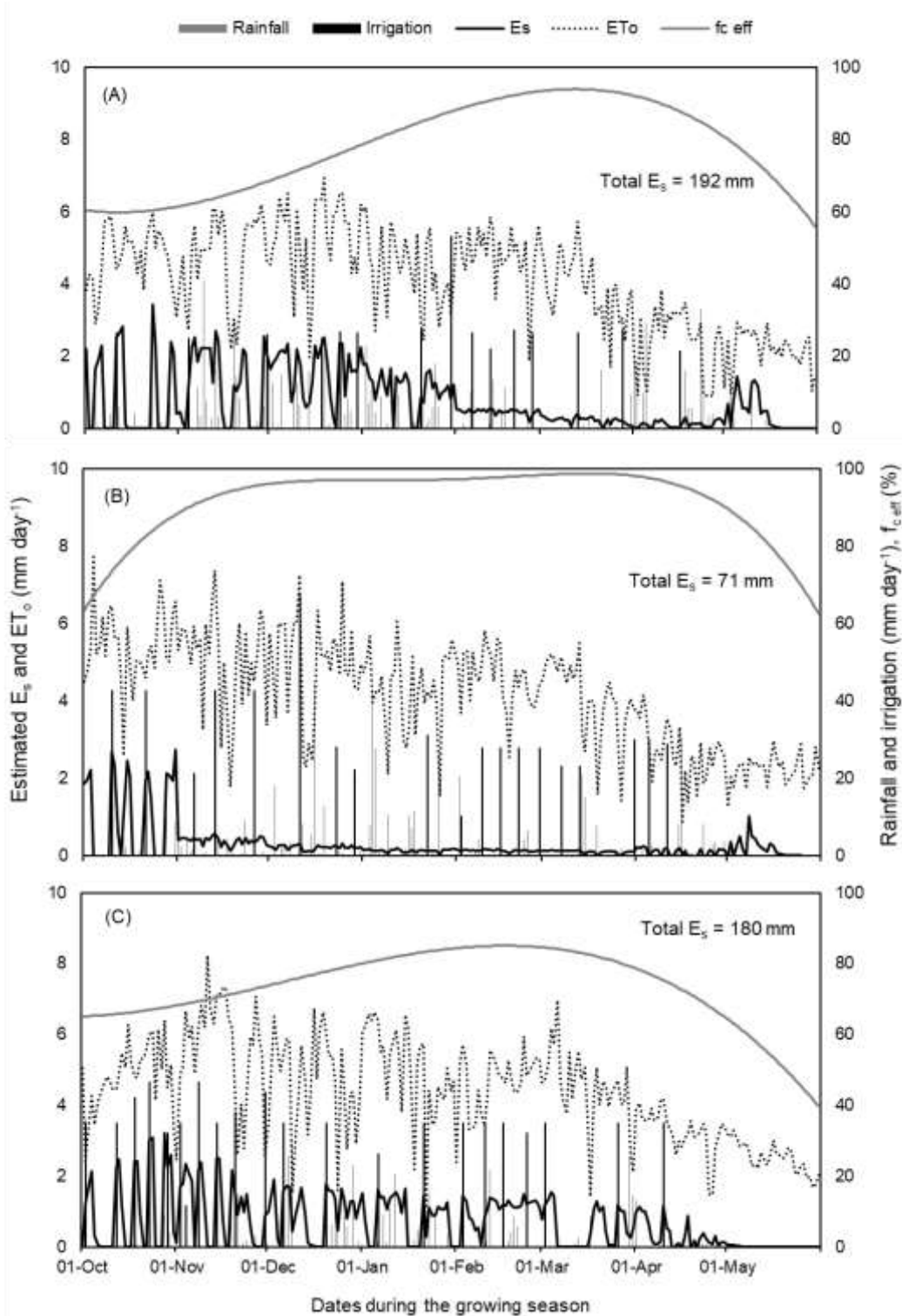


Figure 6.8 Daily soil evaporation (E_s) estimated using the FAO-56 dual K_c model for the (A) 2009/2010, (B) 2010/2011 and (C) 2012/2012 growing seasons in the mature, micro-sprinkler irrigated pecan orchard at Cullinan, as affected by changes in atmospheric evaporative demand (ET_0), canopy cover ($f_{c,eff}$) and rainfall and irrigation events.

Daily E_s rates in the young pecan orchard at Hatfield were less variable throughout the season as compared to the mature pecan orchard at Cullinan, probably due to the fact that the young orchard had much lower $f_{c\text{ eff}}$ (maximum values between 0.12 and 0.18) compared to the mature orchard (maximum $f_{c\text{ eff}}$ between 0.82 and 0.98). As a result, a greater proportion of solar radiation reached the soil surface, which in turn resulted in constantly high rates of E_s . Seasonal E_s was considerably higher in the young orchard (between 273 and 336 mm) than in the mature orchard (between 71 and 192 mm), despite the fact that the young orchard was drip irrigated with a smaller fraction of the soil surface wetted by irrigation and having 60% of the ground partially covered by grass and grass residues. Daily average and seasonal E_s were higher for the young pecan orchard with tree spacing of 10 m x 10 m (1.4 mm day⁻¹ and 336 mm or 80% of ET), as compared to the orchard with a tree spacing of 5 m x 10 m (1.1 mm day⁻¹ and 273 mm or 70% of ET), which was attributed to the difference in $f_{c\text{ eff}}$ between the two orchards (Figure 6.9A and B). Thus, of all the different factors affecting E_s , canopy size was the most dominant in controlling E_s of pecan orchards in this study.

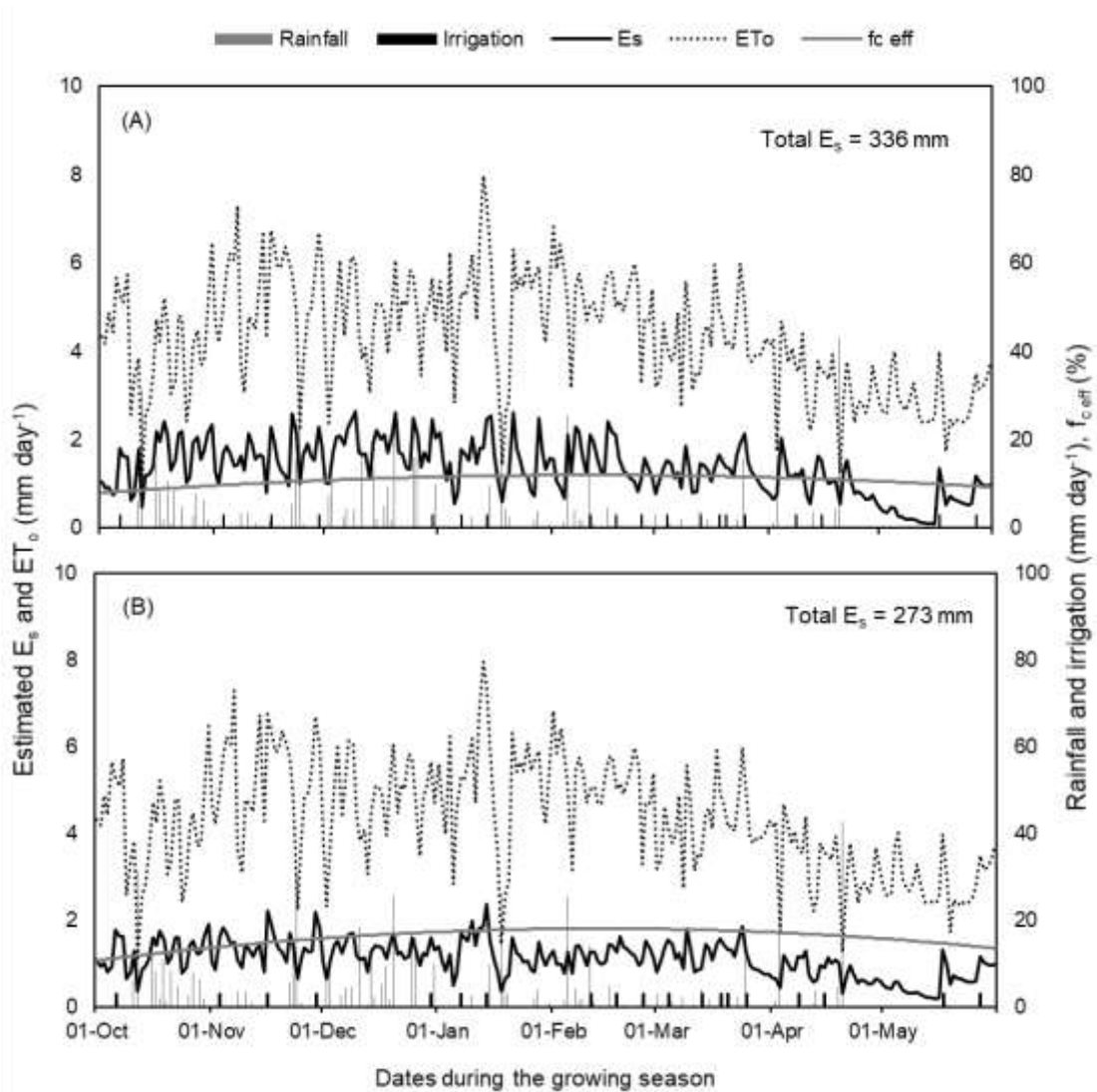


Figure 6.9 Daily soil evaporation (E_s) estimated using the FAO-56 dual K_c model in drip irrigated, young pecan trees, spaced at (A) 10 m x 10 m and (B) 5 m x 10 m, as affected by changes in atmospheric evaporative demand (ET_0), canopy cover ($f_{c\ eff}$) and rainfall and irrigation events during the 2012/2013 growing season at Hatfield.

Seasonal E_s was quite high in the 6-year-old, drip irrigated macadamia orchard, varying between 367 and 370 mm in the two seasons of measurements. Several factors contributed to increased E_s losses in this orchard, including the high frequency and volume of irrigation events and the presence of an active ground cover. The variability of daily E_s throughout the season was predominantly influenced by atmospheric evaporative demand, followed by the occurrence of rainfall and irrigation

events. Thus, the highest daily E_s rates occurred during the rainy season (September to May), under conditions of high ET_o , rainfall and irrigation (Figure 6.10). Variability of seasonal E_s , on the other hand, was more influenced by changes in canopy size from one season to another, being higher during the 2010/2011 season (370 mm, with lower $f_{c\text{ eff}}$, varying between 28 and 60%) and lower during the 2011/2012 season (367 mm, with $f_{c\text{ eff}}$ varying between 35 and 75%).

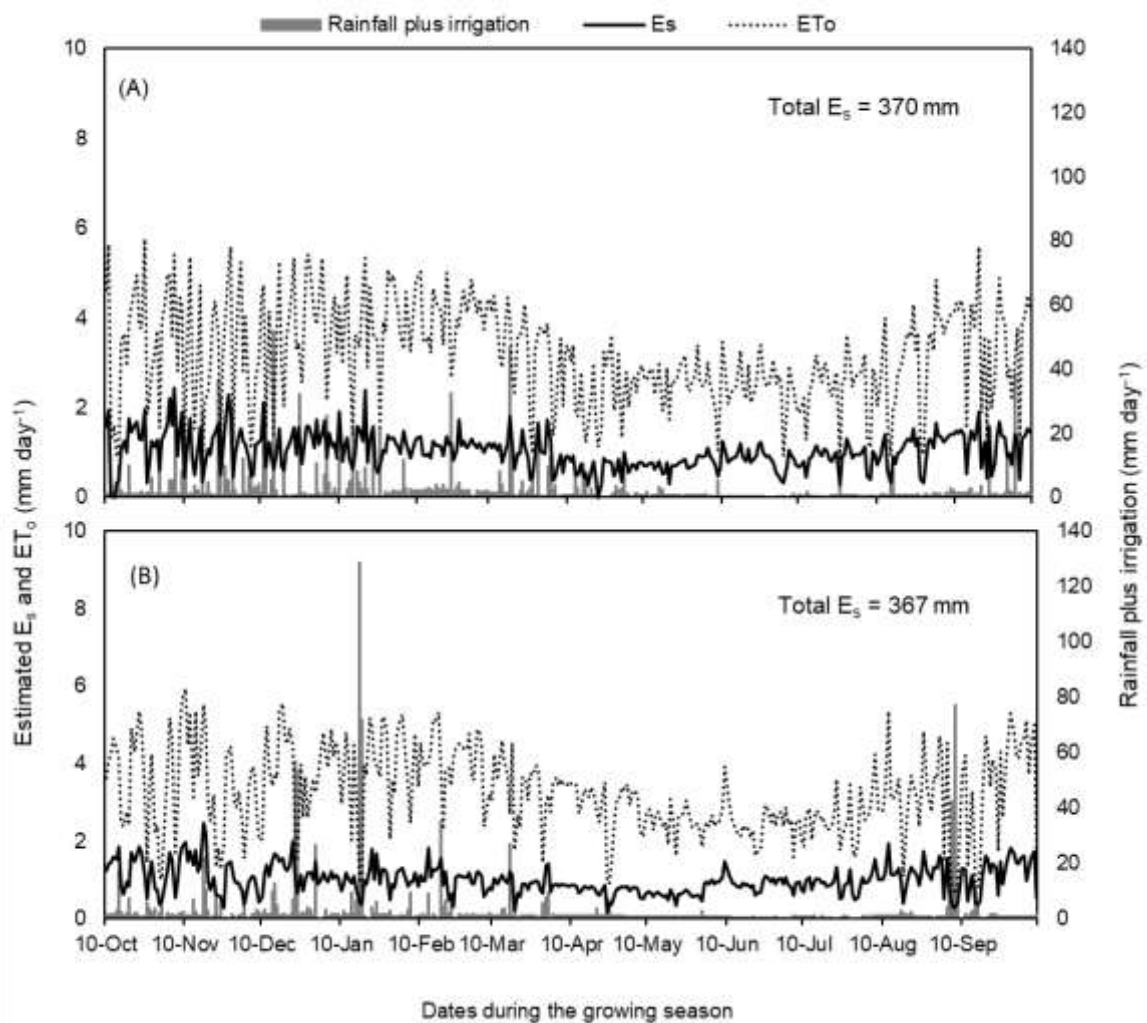


Figure 6.10 Daily soil evaporation (E_s) estimated using the FAO-56 dual K_c model in the drip irrigated, young macadamia orchard as affected by changes in atmospheric evaporative demand (ET_o) and rainfall and irrigation events during the (A) 2010/2011 season and (B) 2011/2012 season at the White River experimental site.

6.3.5 Scenarios of soil evaporation modelling

Possible irrigation water savings through reduced E_s were evaluated in mature and young tree nut orchards, irrigated with micro-sprinkler and drip irrigation (Figure 6.11). Modelling scenarios consisted of an application of a layer of mulch in the area wetted by irrigation, as compared to the actual management practice by the grower, which was to keep the area wetted by irrigation free of any vegetation or mulch.

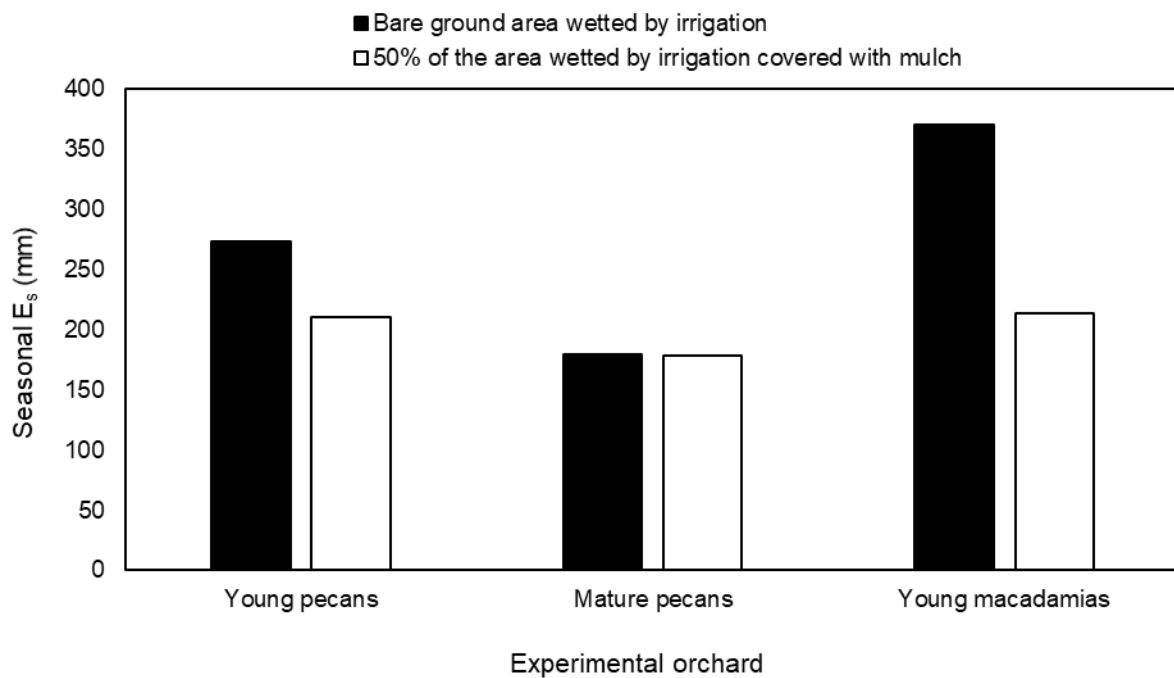


Figure 6.11 Seasonal soil evaporation (E_s) modelled under different scenarios of orchard-floor management in different experimental orchards.

As evident in Figure 6.11, there was considerable reduction in seasonal E_s in both young orchards (from 273 – 370 mm to 210 – 214 mm) due to the application of mulch to cover 50% of the surface area wetted by irrigation, while for the mature orchard the benefits were negligible. This is expected, as young orchards had much lower $f_{c\ eff}$, which resulted in greater energy reaching the ground for E_s as compared to the mature orchard. The suppression of E_s through mulch application was more effective in the young macadamia orchard (42%) compared to the young pecan orchard (23%), which is likely to be the result of higher irrigation frequencies in the former (two to three times daily) compared to the latter orchard (only once per week). A negligible reduction in

E_s was found in the mature pecan orchard with mulch application on the area wetted by irrigation, as the most limiting factor for E_s in this closed-canopy orchard was the amount of available energy on the soil surface and not the wetted fraction of the soil surface. Thus, application of mulch on the surface area wetted by irrigation, only offers potential for reducing E_s in young orchards, particularly for those which are irrigated at high frequencies. As the trees grow older, E_s tends to be limited by the available energy reaching the soil surface and less dependent on the wetted fraction of the soil surface, as most of the orchard floor becomes shaded by the tree canopy.

6.4 CONCLUSIONS

Soil evaporation was measured in pecan and macadamia orchards for 10 to 14 days using micro-lysimeters, and the data was used to successfully parameterize and validate the FAO-56 dual K_c model, in order to estimate soil evaporation throughout the entire growing season. The sensitivity response of the different model input parameters varied across a range of conditions, indicating that E_s was most affected by the canopy cover ($f_{c\text{ eff}}$) and fraction of the soil surface wetted by irrigation (f_w). In closed-canopy orchards it is crucial that good measurements of $f_{c\text{ eff}}$ are made, while in open-canopy orchards adequate measurements of f_w should be conducted for accurate estimates of E_s using the FAO-56 dual K_c model.

Soil evaporation was both spatially and temporally variable. A number of factors played a major role in controlling the spatial distribution of E_s in these orchards, with the most dominant factors being canopy size, water content of the top soil surface layer and the type of ground cover. Temporal changes in E_s throughout the day were strongly influenced by fluctuations in atmospheric evaporative demand, with the most dominant atmospheric variable being solar radiation, while changes of E_s throughout the season were predominantly affected by the atmospheric evaporative demand and water content of the top soil surface layer.

The high variability of E_s in orchard crops suggests that E_s should be modelled separately from transpiration. This would allow the adoption of better irrigation water saving management strategies by the grower, where one option could be to apply a layer of mulch on the wetted surface area by irrigation. In addition, the effects of

climate and orchard management practices on the variability of E_s would be better accounted for, which would allow robust ET predictions on a daily basis for improved irrigation scheduling. However, for irrigation planning purposes, in which longer time-step modelling is usually sufficient for accurate predictions of crop water use, simple approaches that model crop evapotranspiration as a whole would perhaps be more appropriate and easily adopted by the grower due to their user-friendliness and requirement of fewer input parameters for implementation.

CHAPTER 7: EVAPOTRANSPIRATION OF PECANS AND MACADAMIAS

7.1 INTRODUCTION

Adequate water supply is crucial for optimal fruit production, with the consequence that the vast majority of nut crop orchards are dependent on irrigation, particularly in arid and semi-arid climates where rainfall is low and erratic. Consequently, irrigation water management and planning, through accurate quantification of crop water use or evapotranspiration (ET, composed of soil evaporation – E_s and whole-tree transpiration – T), become vital for maximization of orchard profitability.

The pecan and macadamia nut industries in South Africa have seen noticeable expansions over the past years (INC, 2015b). Their contribution to the gross economy of the country considerably increased as a result of increased production (recently reported as 5 918 t of kernel for pecans and 24 230 t of kernel for macadamias, INC, 2015a; SAMAC, 2017a). Moreover, South Africa has become the leading exporter of macadamias and the fourth largest exporter of pecans in the world (NAMC and DAFF, 2013; INC, 2015b), which encourages expansion of the cultivated area with these crops. The latest statistics indicate that there is at least 20 000 ha planted with pecan trees and 28 000 ha planted with macadamia trees, registering a yearly expansion of 2 to 3% for pecans and 8% for macadamias (A. Coetzee, personal communication, 24 August, 2017; SAMAC, 2017b). As the production area increases, the demand for water supply also increases, and presently, there is limited knowledge of pecan and macadamia orchard water requirements under South African soil and climatic conditions. As a result, water resource management and planning of pecan and macadamia orchards are primarily based on the findings obtained from other parts of the world or from water use estimates determined using existing empirical models. This may not be applicable to a wide range of conditions and may lead to incorrect water supply estimates and poor irrigation scheduling (de Villiers and Joubert, 2008). The ET of pecans has been largely studied in New Mexico, under arid climatic conditions and where flood irrigation is used as the main source of irrigation water supply. Under such conditions, seasonal pecan ET has been reported to vary between

368 and 1307 mm, with maximum crop coefficient (K_c) values ranging between 0.57 and 1.39 for young to mature trees, respectively (Miyamoto, 1983; Steinberg *et al.* 1990; Sammis *et al.* 2004). A good relationship was found between daily K_c values of flood irrigated mature pecans growing in New Mexico and daily accumulated Growing Degree Days (GDD), which allowed adjustment of pecan K_c values to specific climatic conditions using thermal time (Sammis *et al.* 2004). Pecan seasonal ET has also been found to be well correlated to maximum canopy cover during the growing season, and as a result, several modelling approaches have been developed in New Mexico to adjust pecan K_c to specific canopy sizes using canopy cover estimates (Miyamoto, 1983; Wang *et al.* 2007; Samani *et al.* 2011). However, none of the past studies reported changes in pecan ET as influenced by canopy cover throughout the growing season, which is important for better validation of crop models and improved irrigation water management. Whilst a number of studies have been documented on pecan ET, there is only one report on ET of macadamias growing in lysimeters in Queensland, Australia, of which mean daily ET of a 12-year-old tree was 75 L day⁻¹ (Stephenson *et al.* 2003).

The K_c and ET of orchard crops are highly variable across different climates and orchard management practices, which include irrigation systems, pruning practices and orchard floor ground cover (Johnson *et al.* 2000; Snyder *et al.* 2000; Johnson and Ayars, 2002; Ayars *et al.* 2003; Williams and Ayars, 2005; Goodwin *et al.* 2006; Wang *et al.* 2007; Samani *et al.* 2011). In this context, various modelling approaches, both generic and specific, have been developed to adjust crop coefficients of pecans 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). Unfortunately, none of these empirical modelling approaches have been evaluated in production regions other than where they were developed, which differ in both the 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. While a number of models have been developed for pecans, but may

not be applicable to growing conditions in South Africa, there are currently no modelling approaches that have been developed to estimate ET of macadamias.

It was hypothesised that pecan ET under the semi-arid, subtropical climate at the experimental sites would be lower than the ET values measured for pecans under an arid climate in New Mexico. Macadamias were expected to use water more efficiently than pecans due to physiological and morphological attributes of the former trees, which favour drought tolerance. As both macadamias and citrus present similar attributes that help regulate T, the ET of macadamias was expected to be accurately predicted using K_c values of citrus. The ET of pecans, on the other hand, was expected to be more accurately estimated with a crop-specific modelling approach than using the generic FAO-56 approach published for stone fruits, due to the occurrence of multiple leaf flushes, particularly in mature trees, which may result in canopy development following more than four stages that is currently suggested for pecans in FAO-56. In order to test these hypotheses, this study aimed to contribute additional knowledge on pecan and macadamia water use, through quantification of crop ET throughout the season in relation to the main drivers of water use under varying weather conditions and orchard management practices. In addition, the FAO-56 approach was evaluated using single K_c values published for stone fruits to estimate monthly ET of pecans and single K_c values published for citrus to estimate monthly ET of macadamias. Moreover, this study validated improved single crop coefficient modelling approaches to estimate monthly ET of pecans and macadamias under varying conditions of climate and canopy cover.

7.2 MATERIALS AND METHODS

7.2.1 Quantification of actual evapotranspiration of pecan and macadamia trees

Actual crop evapotranspiration (ET) of the 37-year-old pecan orchard and the 6-year-old macadamia orchard during the experimental period was estimated as the sum of T and E_s . Transpiration was measured continuously with a calibrated heat ratio method as described by Burgess *et al.* (2001) and Taylor *et al.* (2015), while E_s was estimated with a successfully calibrated and validated FAO-56 dual crop coefficient model, using one to four window periods of E_s measurements at the experimental sites, as

described in Chapter 6. Actual ET quantified in this way was subsequently used to test generic and specific modelling approaches of the FAO-56 to estimate monthly ET of pecans and macadamias. Monthly estimates of crop ET were determined, as they will be useful for planning of irrigation water needs for these orchard crops.

7.2.2 Modelling of monthly crop evapotranspiration using single crop coefficient approaches

Two different modelling approaches, which use single K_c values and grass reference evapotranspiration (ET_o), were selected to estimate ET of pecans and macadamias on a monthly basis: (1) the generic FAO-56 model and (2) a crop-specific model. The evaluation of model performance to estimate ET was conducted using independent data sets obtained from measurements in different growing seasons, in well-managed orchards as described in Chapter 3 of general material and methods, Section 3.1.

7.2.2.1 The generic FAO-56 model

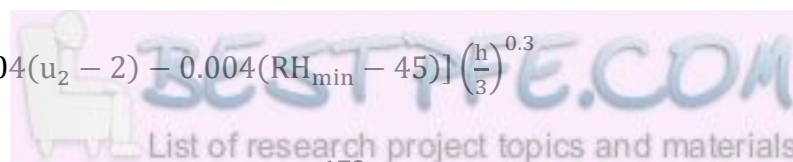
The FAO-56 single crop coefficient approach was used to model monthly crop ET with a single, monthly average K_c value multiplied by the monthly total ET_o , following the equation below (Allen *et al.* 1998):

$$ET = K_c ET_o \quad (7.1)$$

Pecans

Monthly ET of pecans was modelled using the FAO-56 single crop coefficient approach with single K_c values for stone fruits (which includes pecans). Tabulated K_c values published in FAO-56 for 3 m tall stone fruit orchards in a sub-humid region were adjusted for specific conditions of climate and crop height at the study area following Equation 7.2, and used for comparison with measured K_c values of pecans (Allen *et al.* 1998):

$$K_c = K_{c(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \left(\frac{h}{3}\right)^{0.3} \quad (7.2)$$



where $K_{c(Tab)}$ is the value for K_c as published by the FAO-56, u_2 is mean value for daily wind speed at a height of 2.0 m in $m\ s^{-1}$, RH_{min} is mean value for daily minimum relative humidity in % and h is mean plant height for each growth stage.

The growing season (defined as when the trees were in leaf – 8 months for pecans), was divided into four general growth stages (initial, crop development, mid-season and late season) using lengths of the various growth stages for deciduous orchards grown at low latitudes, as provided by Allen *et al.* (1998). The K_c curve was then constructed by connecting straight-line segments through each of the four growth stages. Daily K_c values were subsequently obtained from these straight lines and used to calculate daily ET values, which were subsequently accumulated to determine monthly ET. For growth stages where K_c varied linearly between the K_c at the end of the previous stage ($K_{c\ prev}$) and the K_c at the beginning of the next stage ($K_{c\ next}$), the following equation was used to estimate daily K_c (Allen *et al.* 1998):

$$K_{c\ i} = K_{c\ prev} + \left[\frac{i - \sum L_{prev}}{L_{stage}} \right] (K_{c\ next} - K_{c\ prev}) \quad (7.3)$$

where i is the day number within the growing season, $K_{c\ i}$ is the K_c on day i , L_{stage} is the length of the stage under consideration in days and $\sum(L_{prev})$ is the sum of lengths of all previous stages in days.

Daily K_c values for the pecan orchard, for three consecutive seasons at Cullinan were calculated from actual data using Equation 7.1. A 10-day running average was subsequently used to illustrate the shape of the K_c curve. The different growth stages illustrated for pecans were subsequently named according to their respective growth and development characteristics, as suggested by Herrera (1990) and Wells (2007). Daily K_c values of pecans obtained from measurements in different seasons were averaged for each growth stage and the resultant time-averaged K_c curve was compared to the FAO-56 K_c curve for stone fruit and to the time-averaged K_c curve for a well-managed, mature pecan orchard in Las Cruces, New Mexico, determined from daily estimates of K_c using a polynomial function developed from measured data

obtained by Sammis *et al.* (2004). Length of the various growth stages for the K_c curve for pecans in New Mexico were also obtained from Sammis *et al.* (2004).

Macadamias

Monthly ET of macadamias was modelled using the FAO-56 single crop coefficient approach with single K_c values for citrus (as there are currently no K_c values published for macadamias, and similarly to the macadamia, citrus is an evergreen crop, with physiological and morphological attributes that help regulate the process of water use, Marin and Angelocci, 2011). Tabulated K_c values published in FAO-56 for 4 m tall citrus growing in a Mediterranean climate, with active ground cover and 70% canopy ($K_{c\text{ ini}} = 0.70$, $K_{c\text{ mid}} = 0.65$ and $K_{c\text{ end}} = 0.70$) were adjusted for crop height (5 m) and the subtropical climate at the study site using Equation 7.2, for comparison with measured K_c values for macadamias. These values were specifically selected because the study orchard also had active ground cover and the maximum canopy varied between 67 – 73% for the two growing seasons of measurements. The growing season (12-month period when the trees were in leaf) was divided into four general growth stages (initial, crop development, mid-season and late season) using lengths of the various growth stages for citrus grown in a Mediterranean climate, as provided by Allen *et al.* (1998). The time-average K_c curve was subsequently constructed following similar procedures as described for pecans, and was afterwards compared with the FAO-56 K_c curve for citrus. Monthly actual ET values were also compared with monthly estimates of ET using the FAO-56 single crop coefficient approach.

7.2.2.2 A crop-specific modelling approach

Pecans

The pecan-specific model from New Mexico was used to estimate monthly ET of pecans by empirically relating crop coefficients to canopy cover, as follows (Samani *et al.* 2011):

$$K_c = (0.6035f_{c\text{ eff}} + 0.4808)K_{c\text{-ref}} \quad (7.4)$$

where $f_{c\text{ eff}}$ is effective fractional cover, estimated on a monthly basis as described in Section 3.3.2, and $K_{c\text{-ref}}$ represents the crop coefficient of a mature reference orchard with an $f_{c\text{ eff}}$ of approximately 80%. Values of $K_{c\text{-ref}}$ (obtained from a mature, well-managed pecan orchard in Las Cruces, New Mexico) are given by Samani *et al.* (2011) on a monthly basis (Table 7.1). These values were offset by 6 months to account for seasons in the southern hemisphere.

Table 7.1 Measured monthly crop coefficients for the reference pecan orchard ($K_{c\text{-ref}}$) given by Samani *et al.* (2011) for New Mexico conditions, which have been offset by 6 months to adjust for the seasons in the southern hemisphere.

	Month									
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	
$K_{c\text{-ref}}$	0.39	0.59	0.87	1.02	1.04	1.24	1.26	0.84	0.39	

Values of $K_{c\text{-ref}}$ to be used in Equation 7.4 vary spatial and temporarily as affected by changes in temperatures, which affect thermal time, and therefore directly impact on canopy development. As a result, in order to illustrate such variations, an empirical equation developed by Sammis *et al.* (2004) for a well-managed mature pecan orchard in Las Cruces, New Mexico (Equation 7.5) was used to determine daily $K_{c\text{-ref}}$ values throughout the season, for three different climatic regions in South Africa, namely Cullinan (semi-arid subtropical), Prieska (Steppe climate) and Upington (desert climate).

$$K_{c\text{-ref}} = -3.9 \times 10^{-12} \text{ GDD}^4 + 1.1 \times 10^{-8} \text{ GDD}^3 - 1.1 \times 10^{-5} \text{ GDD}^2 + 4.3 \times 10^{-3} \text{ GDD} + 3.3 \times 10^{-1} \quad (7.5)$$

Growing Degree Days (GDD) were determined from long-term climate data for a specific region, using a base temperature of 15.5 °C and no cut off temperature (Miyamoto, 1983). The limitations of using this method to adjust $K_{c\text{-ref}}$ values for specific climates were illustrated, and consequently a new method was proposed, in which $K_{c\text{-ref}}$ values given by Samani *et al.* (2011) in Table 7.1 for New Mexico conditions, were locally adjusted based on site observations of the beginning and end of the different stages of canopy growth and development of pecan trees, using a six stage crop growth curve, determined from measured data obtained for pecans during the

2009/2010 growing season at the study site. The following steps were used to adjust K_{c-ref} values to specific climatic conditions using this method:

1. List the dates of the growing season from bud-break until complete leaf fall.
2. Number the different dates in an increased order starting from one.
3. Divide the growing period into six growth stages, as defined in Table 7.2. This is done based on actual observations of growth and development of pecan trees conducted by the grower or based on their experience with the occurrence of the different stages throughout the season.
4. Place the point values where K_{c-ref} is constant throughout the growth stage, as illustrated in Table 7.2 for the following stages: bud-break, pollination to early dough and shuck split.
5. Estimate daily K_{c-ref} values for the growth stages where K_{c-ref} varies linearly with day number within the growing season, using Equation 7.3.

Table 7.2 Pecan growth stages throughout the season when the trees are in leaf as defined by Herrera (1990) and Wells (2007). Values of K_{c-ref} throughout the growing season were published by Samani *et al.* (2011).

Pecan growth stage	Definition	K_{c-ref}
1. Bud-break	Emergence of leaf primordial	0.39
2. Pre-pollination	Occurrence of leaf expansion	0.39-1.02
3. Pollination to early dough	Stigmas of pistillate flowers turn from green to red/brown until shell hardening is complete	1.02
4. Dough stage	Kernel is completely formed	1.02-1.26
5. Shuck or Hull split	Sutures of shuck begin to split apart	1.26
6. Leaf drop	Leaves begin to dehisce from the trees	1.26-0.39

Climate-adjusted K_{c-ref} values, based on growth and canopy development observations in pecan trees conducted during the 2009/2010 growing season, were subsequently used to estimate K_c of pecans for the following two consecutive seasons of measurements at the study area using the model described in Equation 7.4. The estimates were then compared to actual values for model validation.

Macadamias

Since there are no existing crop coefficient modelling approaches specifically formulated to estimate ET of macadamias, single crop coefficients determined for macadamias during the 2010/2011 growing season were used to determine time-average macadamia-specific crop coefficients ($K_{c\text{ ini}} = 0.71$, $K_{c\text{ mid}} = 0.72$ and $K_{c\text{ end}} = 0.67$) in order to estimate monthly ET of the crop in the subsequent growing season 2011/2012 using Equation 7.1. The results were then compared with monthly ET measured for macadamias during the 2011/2012 season. Values of $K_{c\text{ mid}}$ for macadamias were developed under 67 -73% $f_{c\text{ eff}}$ (which corresponds to approximately $5.0\text{ m}^2\text{ m}^{-2}$ LAI). For orchards with lower $f_{c\text{ eff}}$ (usually with $\text{LAI} < 3.0\text{ m}^2\text{ m}^{-2}$), the value of K_c can be adjusted by multiplying K_c values under $\text{LAI} < 3.0\text{ m}^2\text{ m}^{-2}$ by the actual $f_{c\text{ eff}}$, as suggested by Allen *et al.* (1998) and Allen and Pereira (2009):

$$K_{c\text{ mid}} = K_{c\text{ min}} + (K_{c\text{ full}} - K_{c\text{ min}}) \left[\min \left[1, 2f_c \cdot (f_{c\text{ eff}})^{\left(\frac{1}{1+h}\right)} \right] \right] \quad (7.6)$$

where $K_{c\text{ mid}}$ is estimated K_c during the mid-season when plant density and/or leaf area are lower than for full cover conditions (usually with $\text{LAI} < 3.0\text{ m}^2\text{ m}^{-2}$), $K_{c\text{ full}}$ is estimated K_c during the mid-season for vegetation having full ground cover or $\text{LAI} \geq 3.0\text{ m}^2\text{ m}^{-2}$, $K_{c\text{ min}}$ is the minimum K_c for bare soil ($\approx 0.15 - 0.20$), h is the tree height (m), f_c is the observed fraction of soil surface that is covered by vegetation as observed from overhead (0.01 – 1).

7.3 RESULTS AND DISCUSSION

7.3.1 Crop evapotranspiration and crop coefficients throughout the growing season

At the beginning of the growing season (October to November) ET of pecans was limited by the size of the canopy and as a result, ET and K_c increased with an increase in fractional interception of photosynthetically active radiation (f_{IPAR}) (Figure 7.1) From December to February, a decline in ET_0 was typically observed, which resulted in a decrease in ET, even though f_{IPAR} was still increasing or was at a maximum. This

decline in both ET and ET_o , resulted in fairly constant K_c values during this period. Evapotranspiration of the mature pecan orchard exceeded ET_o from March to April, when f_{IPAR} reached a maximum. This increase in f_{IPAR} can be explained by the occurrence of a second flush of leaves on the pecan trees at this time, resulting in an increase in the leaf area. This resulted in an increase in K_c values up to a maximum of between 1.2 and 1.38 in the mature pecan orchard. Finally, ET decreased towards the end of the season (May) as ET_o decreased and leaf senescence began, which led to a decrease in K_c . Whilst the maximum K_c values may seem very high, similar large values for K_c ($K_c = 1.39$) have been reported in New Mexico for mature pecans (Miyamoto 1983) and Allen *et al.* (2011a) noted that in a semi-arid environment exceptionally high K_c values of 1.4 can be found for tall, well-watered vegetation.

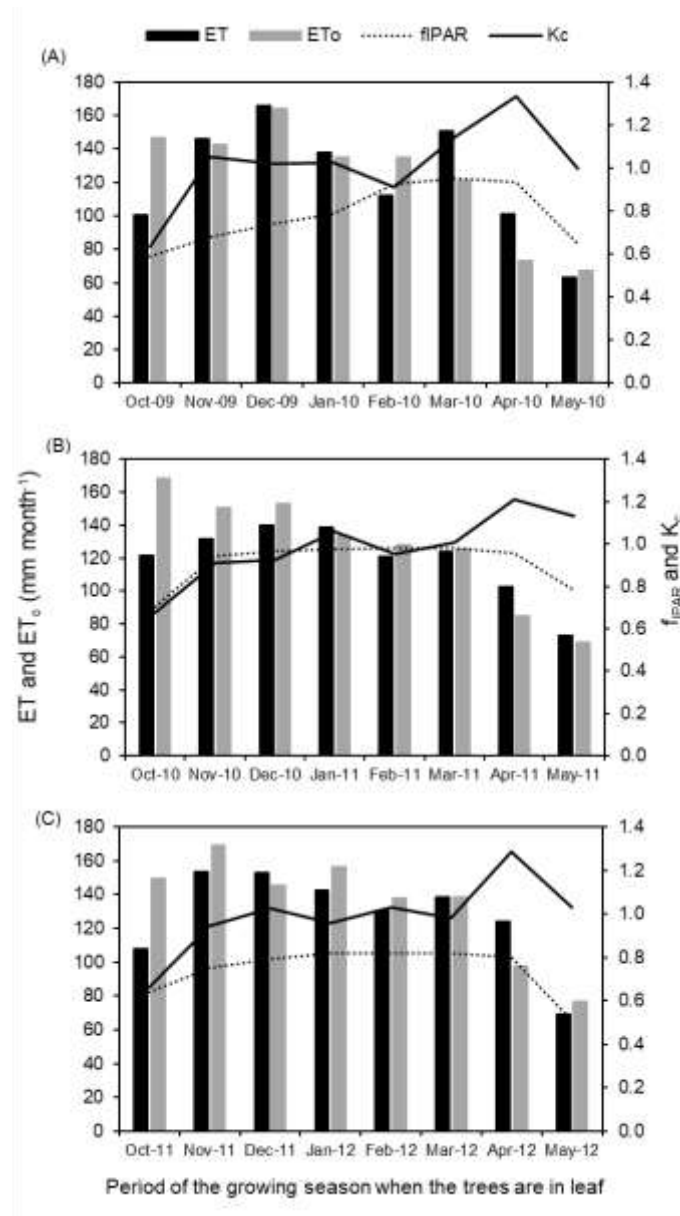


Figure 7.1 Monthly actual evapotranspiration (ET) and crop coefficients (K_c) of a 37-year-old pecan orchard during the (A) 2009/2010, (B) 2010/2011 and (C) 2011/2012 seasons, in relation to atmospheric evaporative demand (ET_o) and fractional interception of photosynthetically active radiation (f_{IPAR}).

When comparing seasonal totals of ET of mature pecans at the study site (1035 mm in 2009/2010, 944 mm in 2010/2011 and 1026 mm in 2011/2012) with estimates from mature orchards in Las Cruces, New Mexico, it is evident that the average ET of pecans at the study site (1000 mm) is lower than average estimates from Las Cruces (1300 mm, Miyamoto, 1983; 1215 mm, Sammis *et al.* 2004). This is not unexpected, as the climate in Las Cruces is dry and arid, characterized by low annual rainfall

(between 203 and 228 mm), low relative humidity, high incident solar radiation and high temperatures during summer, resulting in higher long-term total seasonal ET_o in Las Cruces (1941 mm, Malm, 2003) as compared to the study area (1583 mm, Schulze and Maharai, 2007). In addition, higher E_s rates are expected in New Mexico, as flood irrigation is employed in comparison to micro-irrigation at the study area.

Crop coefficients for the 6-year-old 'Beaumont' macadamia orchard varied from 0.62 to 0.77 during the measurement period (Figure 7.2), while seasonal totals of ET varied from 821 mm during the 2010/2011 season to 846 mm during the 2011/2012 season. Both K_c and seasonal ET values of macadamias were lower than those determined for pecans. The differences in the magnitude of K_c and ET values are likely related to physiological and morphological differences between these two distinct fruit tree species. Macadamias, like other evergreen species, generally have smaller fluctuations in leaf water potentials and leaf water content per unit of dry mass throughout the season, than leaves of pecans and other deciduous species (Sobrado, 1986; Sobrado, 1991). This explains why drought tolerant fruit tree species such as macadamias and other evergreen species like citrus and olives, have adaptation mechanisms to prevent the occurrence of xylem embolism and cavitation through stomatal regulation (Poggi *et al.* 2007; Ennajeh *et al.* 2008), resulting in a more gradual use of soil water even under conditions of non-limited soil water supply (Sperry, 2000). Such physiological adaptations of evergreen species are mainly attributed to their leaves which are sclerophyllous or xeromorphous, with sclerified bundle sheet tissue, a wax coating, pubescence and/or a leathery texture, which all create a barrier against water loss (Sobrado, 1986). Evergreen species, such as citrus, may also have high internal resistances to water movement, which may limit their ability to supply water to leaves as demanded by the atmosphere (Rousseaux *et al.* 2009; Marin and Angelocci, 2011). Marsal *et al.* (2014) further suggested that fruit tree species with higher vegetative vigour (faster, continuous growing shoots, as seen in deciduous species like pecans) generally have larger values of maximum hydraulic conductance, which may lead to higher maximum rates of ET and therefore K_c as compared to evergreen species.

The fairly consistent K_c and ET values of macadamia trees across different seasons (Figure 7.2) is typical of most evergreen crops, where there are no dramatic changes

in canopy size for the majority of the growing season. The canopy size of the 6-year-old macadamia orchard increased slightly during winter and spring (0.4 – 0.6), where after it remained fairly constant for the rest of the growing season (0.6 – 0.7). Values of K_c of macadamias practically did not change during the growing season (0.62 – 0.76 during the 2010/2011 season and 0.65 – 0.77 during the 2011/2012 season). Only a slight drop in K_c values was observed in both growing seasons during summer (from December to March when ET_o was the highest), being more pronounced during the first season of measurements (minimum $K_c = 0.62$) compared to the second season (minimum $K_c = 0.70$). This was attributed to a lower increase in ET relative to ET_o during this period, as compared to the second season (Figure 7.2). A decrease in K_c values during summer was also found in olives (Villalobos *et al.* 2000) and citrus (Snyder and O'Connell, 2007). The drop in K_c values in olive and citrus orchards during summer was attributed to a decrease in E_s due to either lower rainfall (Villalobos *et al.* 2000) or lower solar radiation incidence on the ground (Snyder and O'Connell, 2007). However, T estimated from sap flow measurements in olive orchard and citrus orchards also revealed relatively low transpiration crop coefficients during summer when ET_o was highest, which was explained by a lower increase in T relative to ET_o during this period (Villalobos *et al.* 2013; Taylor *et al.* 2015). This was attributed to increased stomatal control over T, to minimise water loss under high evaporative demands. A similar tendency of regulation of T during summer was also evident in macadamia trees in this study. Jones *et al.* (1985) described it as a general behaviour in fruit tree species due to their strong coupling of stomata with the atmosphere, which is partly explained by the poor hydraulic conductivity of their root systems. The amount of water lost through T in these crops is not always replenished at a sufficient rate when atmospheric demand is high (Pretorius and Wand, 2003). This might have an impact on T and ET predictions using a crop coefficient approach, particularly when estimates are conducted on a daily or shorter time steps.

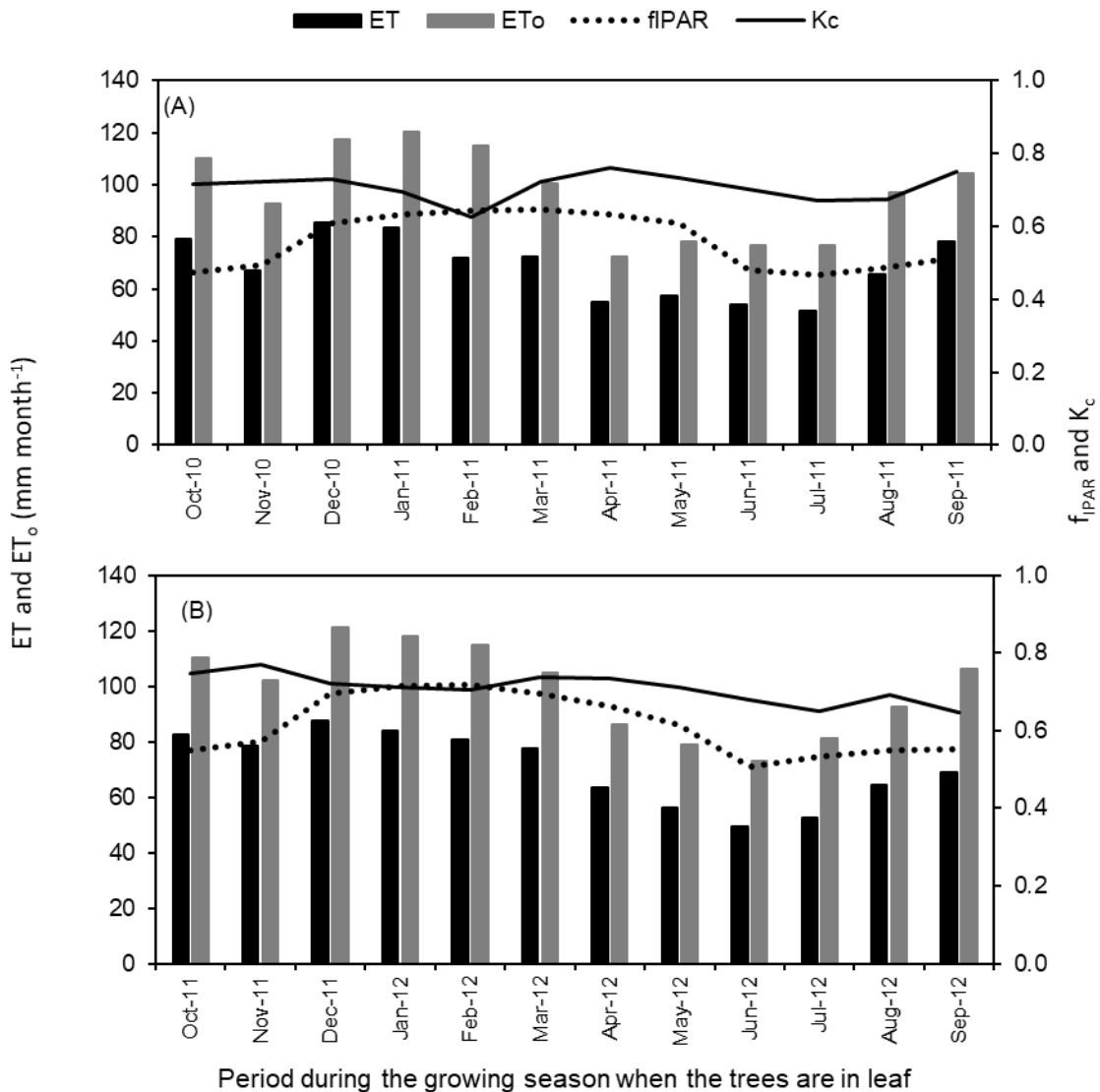
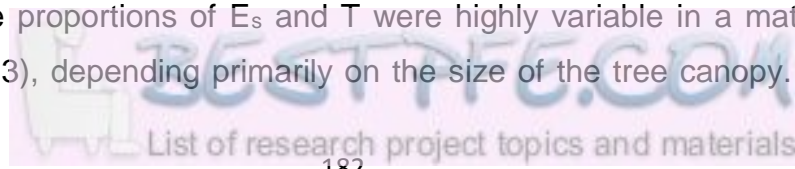


Figure 7.2 Monthly actual evapotranspiration (ET) and crop coefficients (K_c) of a 6-year-old macadamia orchard during the (A) 2010/2011 and (B) 2011/2012 seasons, in relation to atmospheric evaporative demand (ET₀) and fractional interception of photosynthetically active radiation (f_{IPAR}).

7.3.2 Evapotranspiration partitioning

Understanding the partitioning of ET (into E_s and T) in orchard crops is useful for accurately determining crop water use in order to improve irrigation scheduling and management. The proportions of E_s and T were highly variable in a mature pecan orchard (Figure 7.3), depending primarily on the size of the tree canopy. In the 37-



year-old, mature pecan orchard, T formed 81 to 93% of total ET, which resulted in variations of seasonal E_s between 7 and 19%. Seasonal E_s was lower under conditions of high canopy cover (maximum $f_{c\text{ eff}} = 98\%$) and higher when canopy cover was reduced (maximum $f_{c\text{ eff}} = 82\%$), as the result of changes in pruning practices in the different growing seasons. Much higher total seasonal E_s (86% of the total ET) was found in the 7-year-old, young pecan orchard, as a result of the lower canopy cover (maximum $f_{c\text{ eff}} = 11 - 14\%$), which also resulted in lower total T (14% of the total ET).

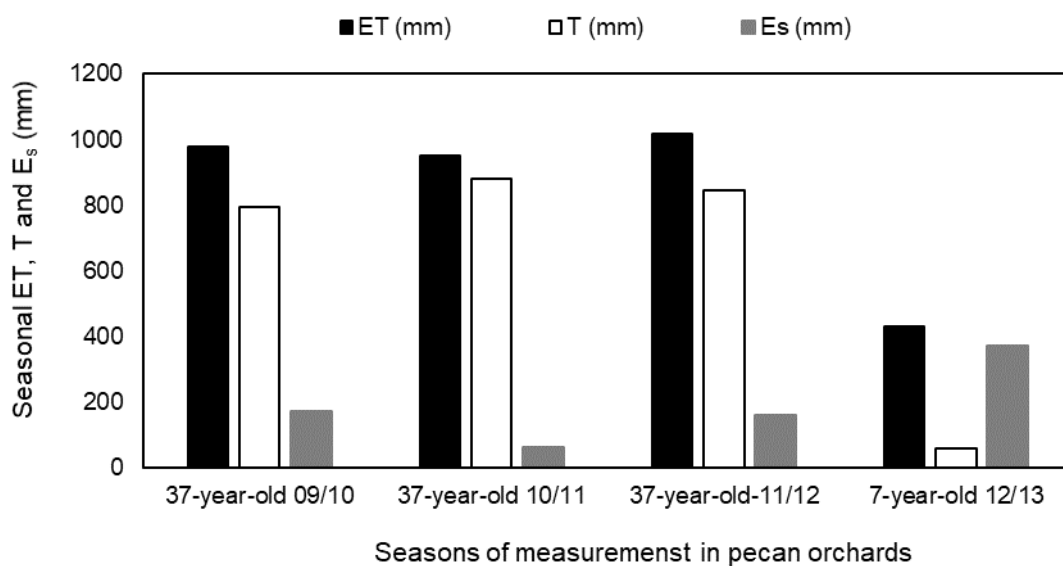


Figure 7.3 Partitioning of crop evapotranspiration (ET) into whole-tree transpiration (T) and soil evaporation (E_s) in the 37-year-old pecan orchard during three consecutive seasons of measurement (2009/2010, 2010/2011 and 2011/2012) at the Cullinan experimental site and in the 7-year-old pecan orchard during the 2012/2013 growing season at the Hatfield experimental site.

Similarly to the pecan orchard, the ET partitioning in the 6-year-old, drip irrigated macadamia orchard was highly influenced by changes in $f_{c\text{ eff}}$. Changes in seasonal ET and its components E_s and T were highly correlated to fluctuations in seasonal average $f_{c\text{ eff}}$, with coefficient of determination (R^2) varying between 0.95 and 0.98 (data not shown). Seasonal ET and T increased with an increase in seasonal average $f_{c\text{ eff}}$, while seasonal E_s showed an opposite trend. The small changes in canopy cover

across seasons of measurement in the macadamia orchard ($f_{c\text{ eff}}$ varied between 0.47 – 0.65 in the 2010/2011 and between 0.51 – 0.71 in the 2011/2012) resulted in minor changes in the proportions of T and E_s of the total ET between the two seasons of measurement (in the 2010/2011: T = 55%; E_s = 45%, similarly to 2011/2012: T = 57%; E_s = 43%, Figure 7.4).

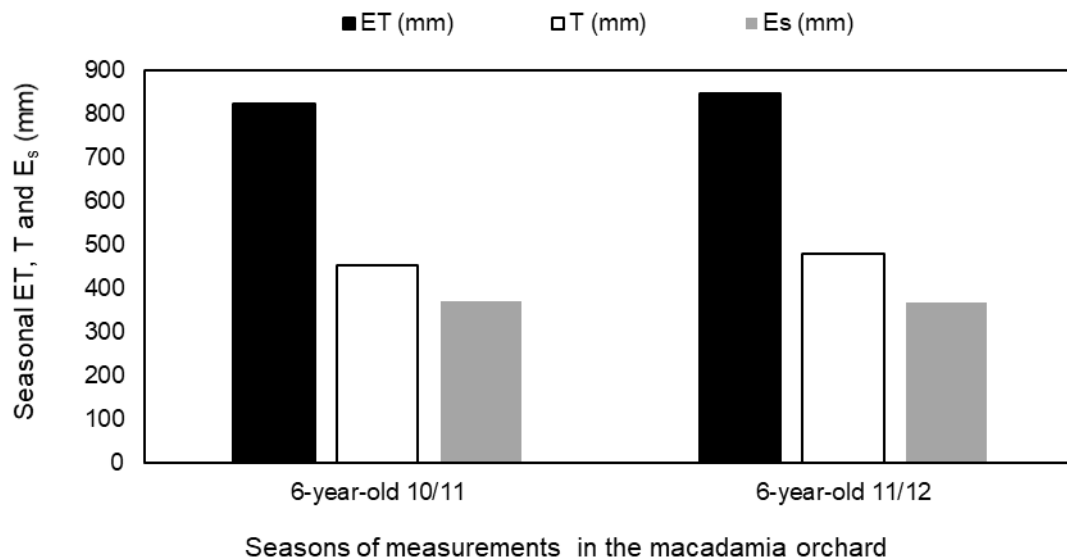


Figure 7.4 Partitioning of crop evapotranspiration (ET) into whole-tree transpiration (T) and soil evaporation (E_s) in the 6-year-old macadamia orchard during two consecutive seasons of measurement (2010/2011 and 2011/2012) at the White River experimental site.

Seasonal E_s was higher in the young macadamia orchard (43 to 45% of the ET) compared to the mature pecan orchard (7 to 19% of the ET), and as a result, more precautions should be taken in young orchards to minimize E_s in order to optimize irrigation applications and maximize water use efficiency of these crops. Reductions of E_s can be achieved through the use of higher planting densities, more efficient irrigation systems such as sub-surface or drip irrigation, low irrigation frequencies, presence of effective ground covers and soil mulches (Jones *et al.* 1985; Fallahi *et al.* 2010). In mature pecan orchards the biggest component of ET is T, and as a result, reducing E_s would make a smaller impact on decreasing the crop ET in order to maximize water use efficiency. Scenario simulations using a successfully

parameterized and validated FAO-56 dual K_c model in this study showed 23 – 42% irrigation water savings in young orchards due to suppression of E_s with an application of mulch in the area wetted by irrigation, while the benefits were negligible in a mature, closed-canopy orchard. Reductions in T , due to waterlogging or water deficits, on the other hand, can severely affect the yield and quality of pecan trees (Garrot *et al.* 1993), as was found in other deciduous tree nut crops such as pistachios and almonds (Goldhammer, 2007). Reduced yield and quality were also observed in macadamia nuts due to water deficits (Stephenson *et al.* 2003) or waterlogging (Trochoulis and Johns, 1992). Thus, appropriate irrigation scheduling will not only maximize crop water use efficiency, but will also ensure optimum crop productivity.

7.3.3 Water use efficiency

Seasonal water use efficiency (defined as the ratio between nut in-shell yield and ET, WUE) of the pecan trees in this study varied between 0.14 kg m⁻³ in an “off-year” and 0.23 kg m⁻³ in an “on-year”, while for macadamia trees it fluctuated between 0.28 and 0.57 kg m⁻³ during the experimental period (Table 7.3). Higher values of WUE in macadamias (average of 0.42 kg m⁻³) compared to pecans (average of 0.19 kg m⁻³) are not surprising, since the macadamia tree presents a conservative water use strategy throughout the entire growing season, under both relatively low and high levels of ET_o , while the pecan tree only shows limited water use under relatively high ET_o levels, as discussed in Chapter 4. Besides, the yields of macadamia trees were also higher on average than the yields of pecan trees (Table 7.3), which could be explained by the differences in their bearing habit. Values of WUE reported for pecans in this study were within the range of those published by Sammis *et al.* (2004) (0.24 kg m⁻³) and Miyamoto (1983) (0.19 kg m⁻³) for well-managed, mature pecans in New Mexico.

Table 7.3 Yield, seasonal water use (ET) and water use efficiency (WUE) of bearing pecan and macadamia trees under non-limiting water supply conditions.

Experimental orchards	Crop yield (kg ha ⁻¹ nut in-shell)	Seasonal ET (mm)	WUE (kg m ⁻³)
<u>37-year-old pecans</u>			
2009/2010	2400	1035	0.23
2010/2011	1300	944	0.14
2011/2012	2000	1026	0.19
<u>6-year-old macadamias</u>			
2010/2011	2300	821	0.28
2011/2012	4800	845	0.57

7.3.4 Crop evapotranspiration estimates using a single crop coefficient approach

7.3.4.1 Modelling ET of pecans using the generic FAO-56 model applied to stone fruit

Monthly actual ET of mature pecans during the 2009/2010, 2010/2011 and 2011/2012 growing seasons were compared to estimated values using the FAO-56 single crop coefficient approach with K_c values published for stone fruit (Allen *et al.* 1998), which were adjusted for specific conditions of climate and crop height at the study site (Figure 7.5).

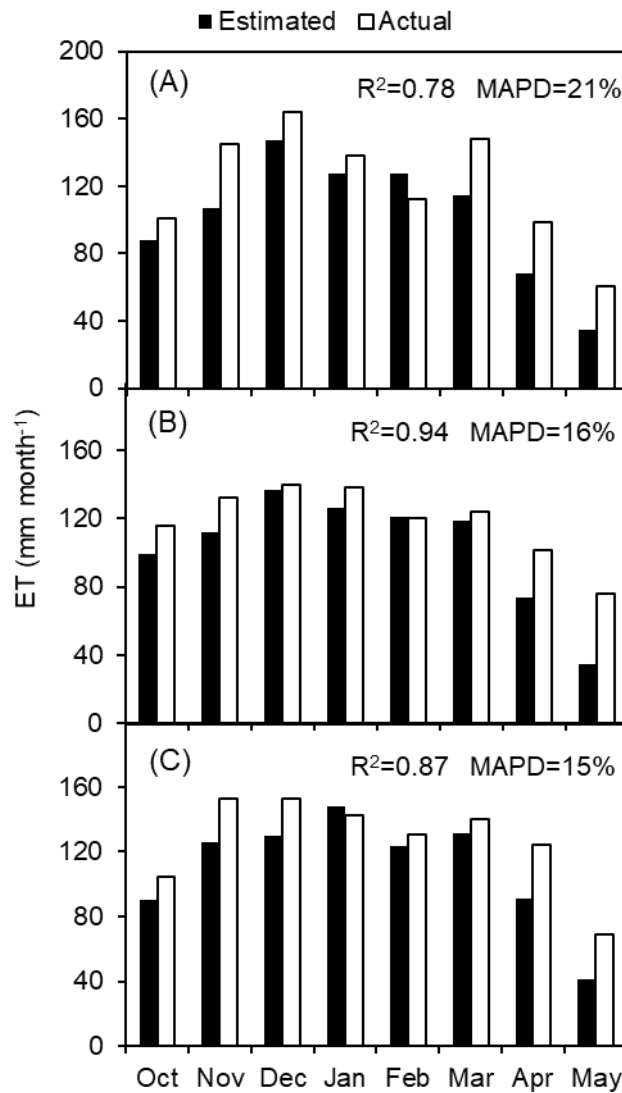


Figure 7.5 Comparison between monthly actual and estimated crop evapotranspiration (ET) using the generic procedure of FAO-56 with climate adjusted single (time-averaged) K_c values published for stone fruits for a mature pecan orchard during the (A) 2009/2010 season, (B) 2010/2011 season and (C) 2011/2012 season at the Cullinan experimental site.

Although the FAO-56 single K_c procedure generally underestimated monthly ET, there was, on average, a fair agreement between monthly estimated and measured ET of mature pecans during the three measurement seasons, with an average MAPD varying between 15 and 21%. However, a more detailed analysis showed inconsistency in model performance when estimating monthly ET throughout the season. Whilst good agreement between measured and predicted ET (MAPD below

15%) was noted for the majority of the growing season (October to March), there was poor agreement (MAPD above 25%) towards the end of the season (April to May). The noticeable differences between measured and estimated ET values of pecans using the generic FAO-56 approach could possibly be attributed to the incorrect shape of the K_c curve (a six stage crop growth curve was observed for pecans at Cullinan, compared to the four stage FAO-56 crop growth curve for stone fruit), inappropriate lengths of the growth stages and differences in magnitude of K_c values when applying parameters for stone fruit to pecans (Figure 7.6). As a result, it is suggested that a crop-specific modelling approach be considered for more accurate estimates of pecan ET.

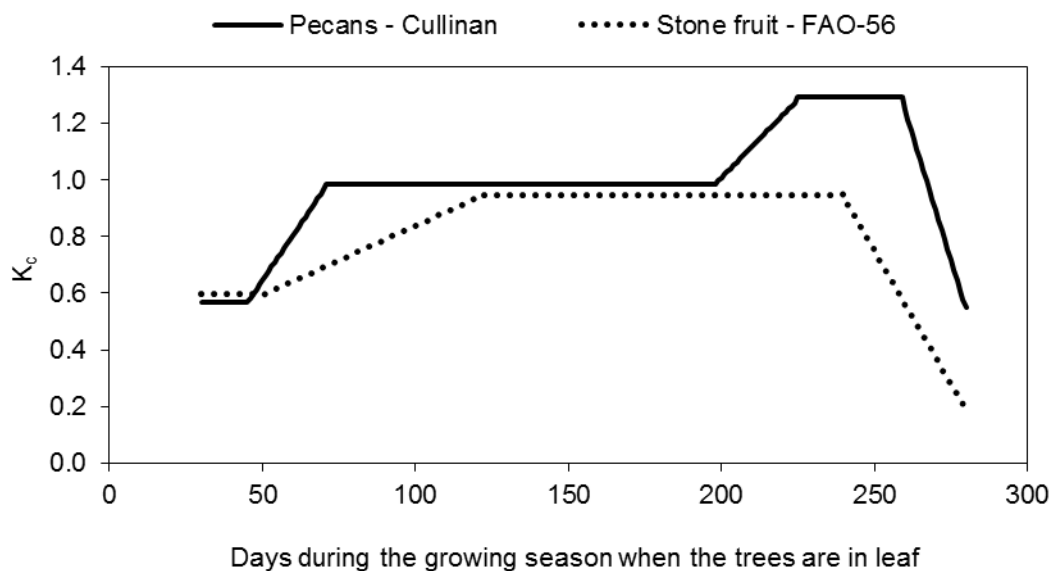


Figure 7.6 A six stage crop coefficient (K_c) curve observed for a well-managed, mature pecan orchard at Cullinan during the 2009/2010 growing season in comparison to the four stage crop coefficient curve published in FAO-56 for stone fruit orchards.

7.3.4.2 Modelling ET of pecans using a crop-specific modelling approach

Initial modelling exercises to predict pecan ET for a mature orchard using the model of Samani *et al.* (2011) in which K_{c-ref} values for New Mexico were offset by 6 months for southern hemisphere seasons and adjusted for actual vegetation according to changes in fractional canopy cover, did not prove to be very successful. These K_{c-ref}

values gave extremely poor predictions of K_c for the different seasons of measurement (R^2 between 0.01 and 0.09), with underestimations at the start and end of the season and overestimations in the middle of the season (MAPD between 42 and 47%) (Figure 7.7A and B). However, when the K_{c-ref} values from New Mexico were adjusted for both actual vegetation and specific conditions of climate at the study site, good predictions of monthly K_c values were obtained (Figure 7.7C and D). This was done following a six stage crop growth curve approach, as observed from measured data during the 2009/2010 growing season at the study site, as well as from previously published measured data for mature pecans (Sammis *et al.* 2004; Samani *et al.* 2011).

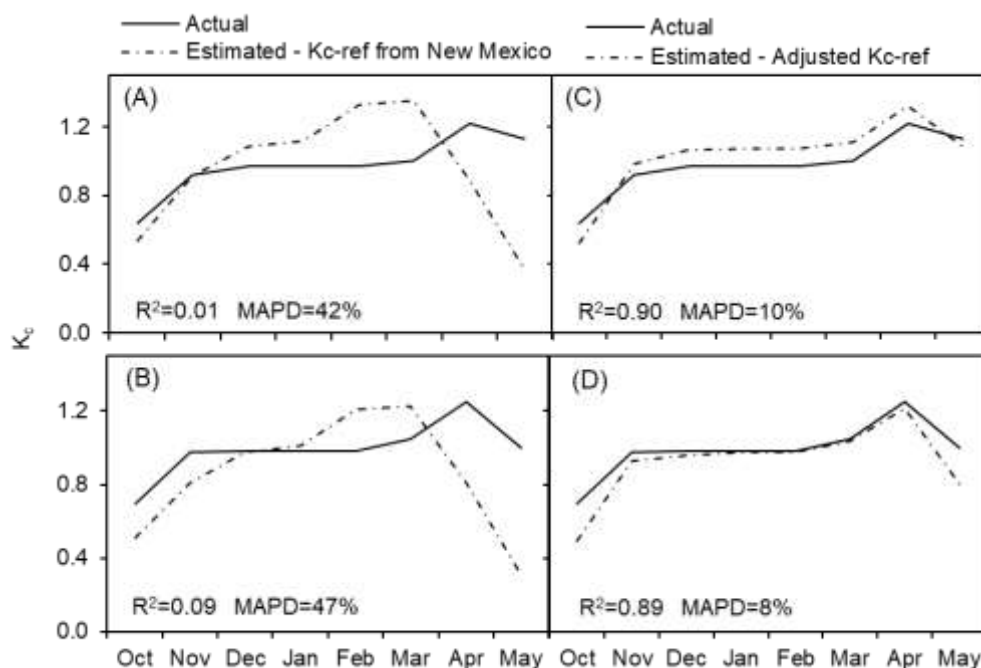


Figure 7.7 Comparison between observed and estimated crop coefficients (K_c) using a pecan-specific single crop coefficient approach with (A, B) reference crop coefficients from New Mexico and (C, D) reference crop coefficients adjusted for climatic conditions at the study site, during the 2010/2011 and 2011/2012 seasons.

Discrepancies between estimated K_c using K_{c-ref} values for pecans in New Mexico and actual K_c values were attributed to differences in K_c curves, as observed in Figure 7.8. Although both pecan K_c curves presented six crop growth stages (which, according to Herrera (1990), Wells (2007) and field observations of pecan nut growth and

development at the study site, can be classified as: 1 - Bud-break; 2 – Pre-pollination; 3 - Pollination to early dough; 4 - Dough stage; 5 - Shuck or hull split and 6 - Leaf drop), the length and magnitudes of K_c values for the different stages differed between the K_c curve for pecans in Cullinan and New Mexico.

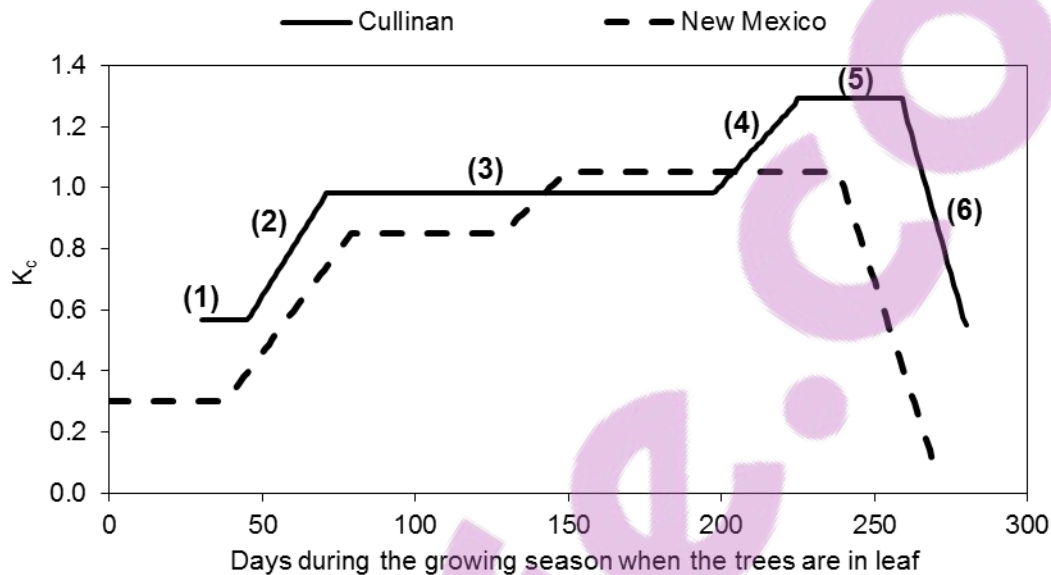


Figure 7.8 Six stage crop coefficient (K_c) curves for a well-managed, mature pecan orchard at Cullinan and New Mexico.

The approach developed by Sammis *et al.* (2004) (a simple polynomial equation), which adjusts pecan K_c values to specific climatic conditions using locally observed Growing Degree Days (GDD), seemed to perform well in adjusting the shape of the K_{c-ref} curve for pecans throughout the season at Cullinan. However, it has potential limitations and may only apply in regions experiencing ambient temperatures within the range in which the equation was generated, such as Cullinan (1100 GDD) (Figure 7.9), with total seasonal accumulated thermal time below or equal to 1500 GDD. In regions with extremely high temperatures and total seasonal accumulated thermal time above 1500 GDD, as is seen in some pecan production areas in South Africa such as Upington (2400 GDD) and Prieska (1600 GDD), this empirical approach will not adjust K_{c-ref} adequately towards the end of the season (Figure 7.9). This may result in poor estimations of ET. This approach is also conservative in terms of the magnitude of K_{c-ref} values (a maximum of 1.1) from which the equation was developed, and thus,

in seasons where maximum K_c exceeds 1.1, the K_c -GDD relationship of Sammis *et al.* (2004) would result in an underestimation of seasonal ET (data not shown).

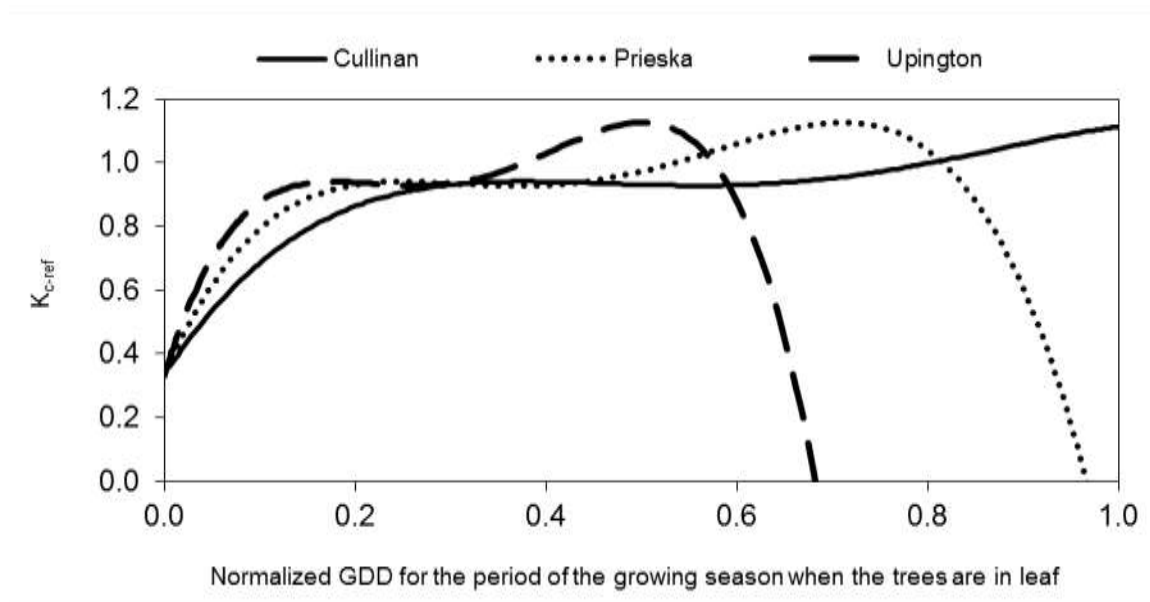


Figure 7.9 Reference crop coefficients (K_{c-ref}) adjusted for specific climatic conditions using Growing Degree Days (GDD) for some of the pecan growing regions in South Africa namely, Cullinan, Prieska and Upington using a simple polynomial function developed by Sammis *et al.* (2004).

Given the limitations presented above using the empirical method of Sammis *et al.* (2004), there was a need to develop an improved method for the adjustment of K_{c-ref} values for pecans growing under a wider range of climates in order to estimate monthly K_c of pecans using the Samani *et al.* (2011) model. With such an intention, a simple method was proposed in this study for adjusting K_{c-ref} values from New Mexico published by Samani *et al.* (2011) to a specific climatic region. This method is based on local observations of the beginning and end of the different stages of canopy growth and development of pecan trees (1 - Bud-break; 2 – Pre-pollination; 3 - Pollination to early dough; 4 - Dough stage; 5 - Shuck or hull split and 6 - Leaf drop), following a six stage crop growth curve approach, as observed from measured data at the study site, as well as from previously published measured data for mature pecans (Sammis *et al.* 2004, Samani *et al.* 2011). This method was validated by comparing actual to estimated values of K_c and ET for a mature pecan orchard at the study site (Figures

7.7C, D and 7.10C, D). Considerable improvements were made in the estimated monthly K_c values (R^2 between 0.89 and 0.90 and MAPD between 8 and 10%), which led to more accurate estimates of monthly (MAPD between actual and estimated values decreased from 25 to 9% on average) and seasonal ET (MAPD between actual and estimated values decreased from 6 to 3% on average). Similar accuracy could not be achieved using K_{c-ref} values from New Mexico without prior adjustment for local climatic conditions, which led to considerable over and underestimations of estimated monthly ET (between 24 and 26% on average) when compared to actual values (Figure 7.10A, B, C). The improvement was particularly evident towards the end of the season, as the season in New Mexico ends with a sudden damaging freeze, resulting in rapid leaf drop. Such a phenomenon is not always experienced at the study site. This demonstrates the importance of appropriate K_{c-ref} values in this empirical approach, and that these values should be adjusted for local climatic conditions, as they are heavily influenced by the rate of canopy development, as advocated by Allen *et al.* (1998) and Samani *et al.* (2011).

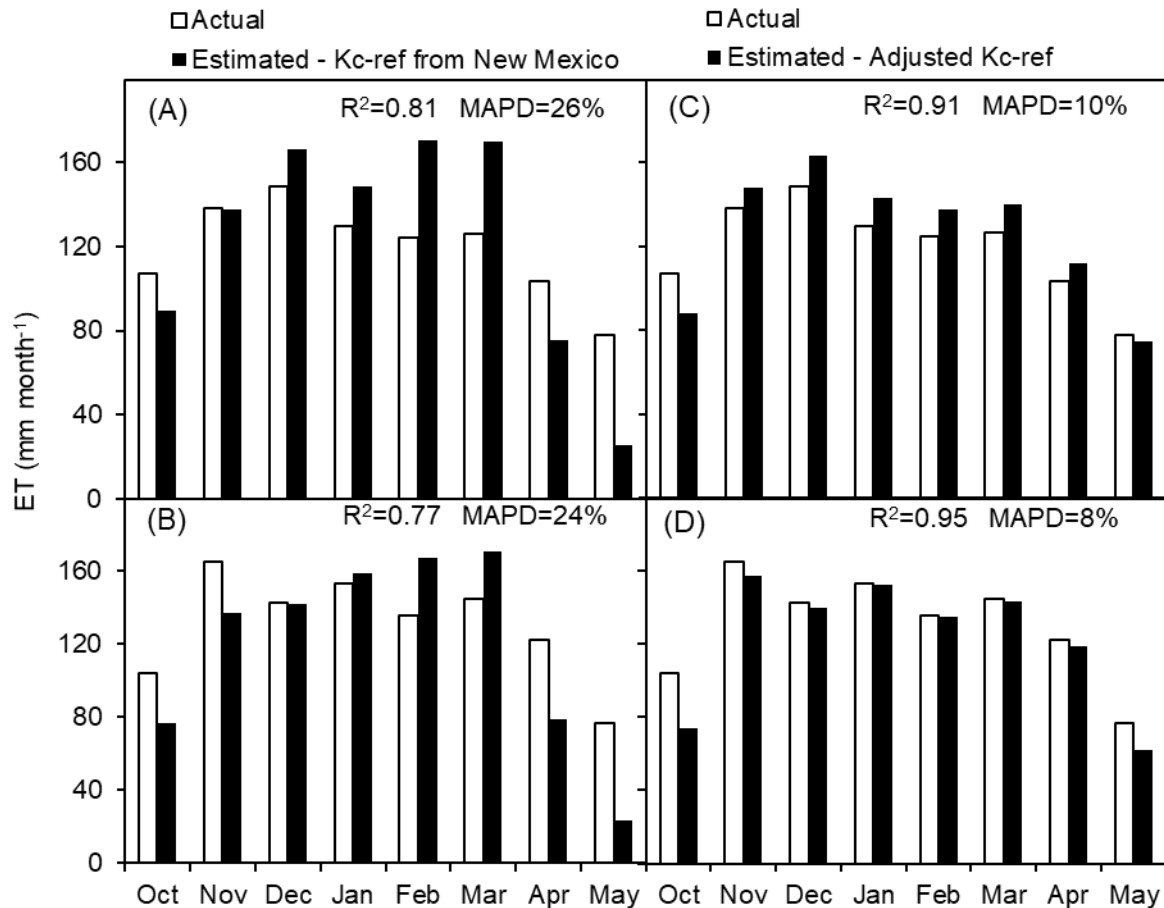


Figure 7.10 Comparison between actual and estimated crop evapotranspiration (ET) using a pecan specific single crop coefficient approach with (A, B) reference crop coefficients (K_{c-ref}) from New Mexico and (C, D) reference crop coefficients adjusted (length of the various growth stages) for climatic conditions at the study site, during the 2010/2011 and 2011/2012 seasons.

7.3.4.3 Modelling ET of macadamias using the generic FAO-56 model with crop coefficients applied to citrus and macadamia-specific crop coefficients

Time-average actual K_c values of macadamias determined from field measurements at the study site were considerably different from those for citrus published in FAO-56 (Figure 7.11). Macadamia trees had lower maximum K_c (0.72) and less variable K_c values throughout the season (0.67 – 0.72) compared to citrus K_c values adjusted for climatic conditions at the study site (maximum K_c = 0.90 and the range of K_c between

0.61 – 0.90. One distinctive feature of the time-average K_c curve for citrus, constructed using values published in FAO-56, was its considerably lower K_c during spring (0.61 – 0.8), summer (0.61) and autumn (0.61 – 0.69) as compared to winter (0.9) (Figures 7.11 and 7.12). Marin and Angelocci (2011) and Taylor *et al.* (2015) also found similar evidence of decreased transpiration crop coefficients (K_t) and K_c values for citrus during wet summer months as compared to dry winter months. These authors attributed such behaviour in citrus to the presence of a strong stomatal regulation and high T coupling to the atmosphere, with vapour pressure deficit being the dominant regular of T. The decrease in K_t and K_c values during wet summer months was less pronounced in macadamias compared to that found in citrus, and as a result such differences between wet summer vs dry winter months were practically unnoticeable in the time-average K_c curve for macadamias. The significant differences in the magnitude and pattern of variability of K_c values between the two evergreen crops throughout the growing season is unexpected, as evergreen fruit tree species generally possess similar morphological and physiological characteristics that enable effective stomatal control of T particularly under conditions of high atmospheric evaporative demand (Carr, 2012a; Carr, 2012b; Carr, 2013; Carr, 2014a; Carr, 2014b). These special attributes include leaves with many xeromorphic or sclerophyllous characteristics such as thick, waxy cuticles with stomata occurring mainly on the lower leaf surface in citrus (Spiegel-Roy and Goldschmidt, 1996), thick cuticle, high pubescence, compact mesophyll cells and stomata covered by dense network of trichomes in olives (Connor, 2005; Rapoport *et al.* 2016), which are quite comparable to sclerified bundle sheath tissues and stomata found only on the abaxial surface of the leaf in macadamias (Stephenson *et al.* 1989; Stephenson and Trochoulis, 1994; Spiegel-Roy and Goldschmidt, 1996; Rapoport *et al.* 2016). Due to the presence of such attributes, the water consumption per unit leaf area in these crops is generally reduced relative to that of deciduous species. The almost constant K_c values in macadamia trees throughout the growing season, which is evident in Figures 7.11 and 7.12, are mainly attributable to constantly low fluctuations in T per unit leaf area in proportion to changes in ET_o , which is likely related to a supply limitation of water to the leaves that results in stomatal closure. Based on the results presented in Figures 7.11 and 7.12, it is clear that the regulation of water use in citrus is markedly different from that in macadamias, despite their similarities in the presence of morphological and physiological attributes that help regulate water loss through the stomata. Citrus

leaves are likely to have stronger restrictions in water loss under high atmospheric water demand conditions compared to cooler periods, while macadamias maintain similar restricted pattern of water loss throughout the growing season.

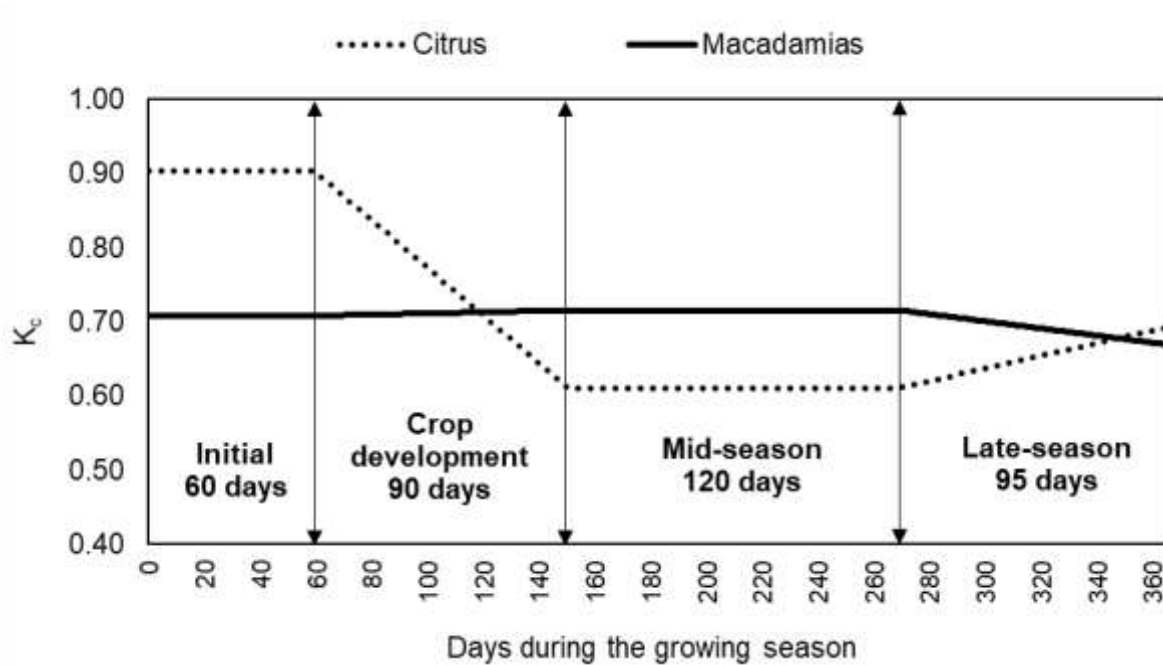


Figure 7.11 Time-average crop coefficient (K_c) curve for macadamias derived from field measurements during the 2010/2011 growing season at the White River experimental site compared to K_c values for citrus derived from time-average K_c values published in FAO-56.

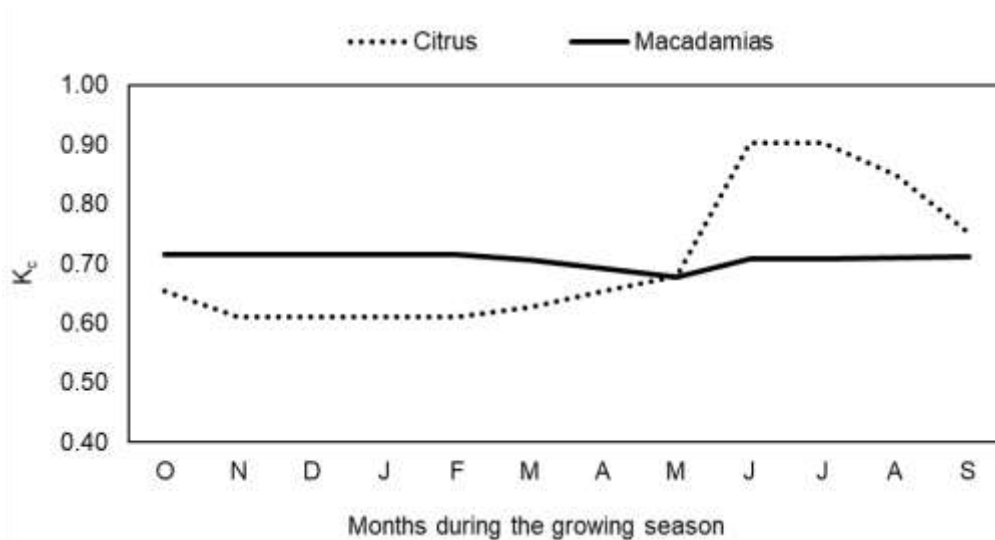


Figure 7.12 Monthly crop coefficients (K_c) for macadamias determined using the time-average K_c curve obtained from field measurements during the 2010/2011 growing season at the White River study site, compared to those of citrus developed from published values in FAO-56.

As a result of considerable discrepancies in K_c values between citrus and macadamias, poor predictions of monthly ET ($R^2 = 0.00$ and MAPD = 20%) were obtained using the generic FAO-56 single K_c approach with K_c values for citrus. However, when macadamia-specific K_c values were used, monthly ET estimates of macadamias were considerably improved throughout the entire growing season (R^2 increased from 0.00 to 0.67 and MAPD reduced from 20 to 9% (Figure 7.13). The macadamia-specific single K_c approach of the FAO-56 validated in this study for orchards with 70% canopy cover can be applied to orchards with smaller canopies by making adjustments for the actual vegetation using measurements of effective fractional canopy cover ($f_{c\text{ eff}}$), following the procedure of Allen *et al.* (1998) described in Section 7.2.2.2.

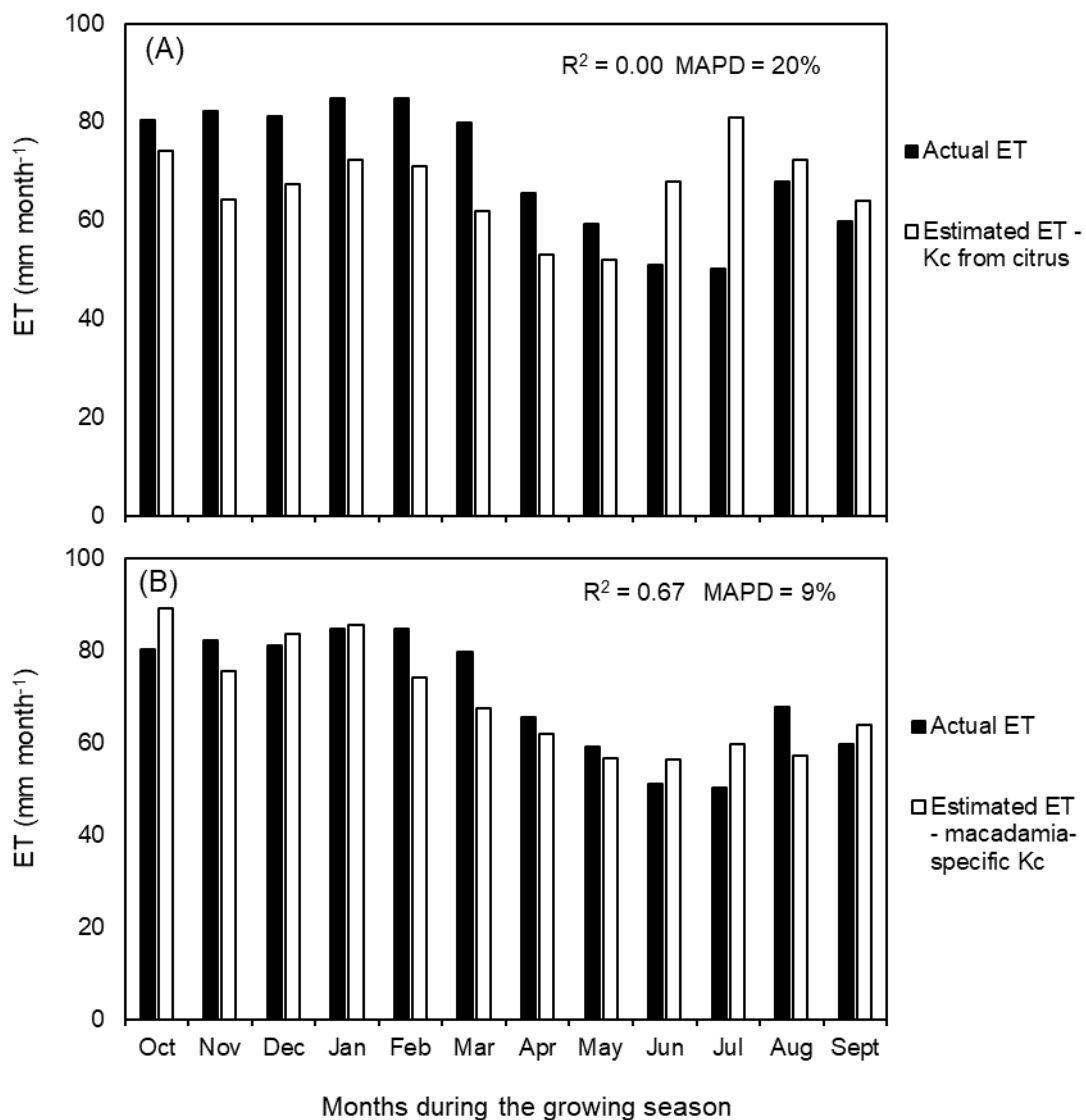


Figure 7.13 Comparison between actual evapotranspiration (ET) of macadamias during the 2011/2012 growing season and ET estimated using the generic FAO-56 model with (A) K_c values for citrus and (B) macadamia-specific K_c values.

7.4 CONCLUSIONS

Seasonal ET of a closed-canopy, mature pecan orchard grown under a semi-arid, subtropical climate at the experimental site was lower (average of three seasons of measurement = 1000 mm) compared to that of a closed-canopy, mature orchard grown under an arid climate in New Mexico (1300 mm). Monthly crop coefficients and

ET values of mature pecans were highly variable throughout the season (0.6 – 1.4 and 60 – 160 mm, respectively) and from one season to another (944 – 1035 mm), being strongly influenced by changes in canopy cover. An opposite trend was evident in young macadamia trees, where there were no dramatic changes in canopy size for the majority of the growing season (as it is an evergreen tree), resulting in fairly constant crop coefficients (0.62 – 0.77), monthly ET totals (52 – 87 mm), as well as seasonal ET values (821 – 846 mm). The conservative water use pattern in macadamia trees might have contributed to higher water use efficiencies in this species (0.28 – 0.57 kg m⁻³) compared to pecan trees (0.14 – 0.23 kg m⁻³). Thus, under limited water supply conditions (in lower rainfall or dry regions with limited irrigation water), it may be appropriate to cultivate larger areas of macadamias rather than pecans in order to save water, while maintaining an adequate production and market supply of nuts.

Seasonal total E_s was higher in young macadamia (43 to 45% of the ET) and pecan orchards (86% of the ET), compared to the mature pecan orchard (7 to 19% of the ET), suggesting that more precautions should be taken in young orchards to minimize E_s in order to optimize irrigation applications and maximize water use efficiency of these crops. In both crops, fluctuations in monthly ET were predominantly controlled by changes in atmospheric evaporative demand, while changes in seasonal ET were strongly dependent on variations in canopy cover, suggesting that a crop coefficient approach could potentially provide good estimates of monthly and seasonal ET for these crops, which could assist with better planning of irrigation in these orchards.

The FAO-56 generic, single crop coefficient modelling approach proved to satisfactorily estimate monthly ET of pecans using time-average K_c values published for stone fruits, but failed to provide acceptable predictions of monthly ET of macadamias when using time-average K_c values published in FAO-56 for citrus. However, when crop-specific K_c values were used, accurate predictions of monthly ET were obtained for both crops. Modelling monthly crop ET was more complex for pecans compared to macadamias, as a result of high variability of K_c values throughout the season and from one season to another in the pecan orchard.

The poor estimates of ET using the generic FAO-56 approach for stone fruit was mainly attributed to the use of a K_c curve with the incorrect shape. Stone fruits follow a four stage K_c curve, whilst a six stage K_c curve was observed for pecans from measurements at the study site, as well as from previously published pecan data. These limitations were partially addressed when using the pecan-specific single K_c modelling approach of Samani *et al.* (2011) in which reference K_c values from a mature, well managed orchard (K_{c-ref}) are adjusted for actual vegetation using measurements of fractional canopy cover. However, the K_{c-ref} values given for New Mexico not only needed to be adjusted for actual vegetation, but also for local climatic conditions, which determine the rate of canopy development. For this purpose, the simple K_c -GDD relationship of Sammis *et al.* (2004) was evaluated across different climatic regions in South Africa, and it was found that this empirical method may only be adequate in regions where seasonally accumulated GDD values do not exceed 1500 GDD, which is the seasonal cumulative thermal time required for a complete pecan production cycle in the region where the equation was developed. As a result, a new method is proposed for constructing a K_{c-ref} curve for pecans in different climatic regions, including those with high temperatures, where seasonal accumulated thermal time for a complete pecan production cycle exceeds 1500 GDD. This can be achieved based on observations of canopy and nut development for various growth stages within the season, following a six stage crop growth curve approach, as determined from measured data obtained in a well-managed, mature pecan orchard at the study site. The pecan-specific single K_c model of Samani *et al.* 2011 was successfully validated to estimate monthly ET of mature pecan orchards using this simple method of adjusting K_{c-ref} for different climatic regions of pecan growth.

Thus, in order to accurately estimate monthly ET of large pecan orchards across a range of climatic conditions, it would be required to adopt the improved version of the pecan-specific modelling approach described in this study. On the other hand, monthly ET of macadamia orchards having leaf area index of $3.0 \text{ m}^2 \text{ m}^{-2}$ and above can accurately be predicted with the generic FAO-56 single crop coefficient approach using macadamia-specific time-average K_c values, and not time-average K_c values published in FAO-56 for citrus. This implies using the following time-average K_c values for macadamias: $K_{c\ ini} = 0.71$, $K_{c\ mid} = 0.72$ and $K_{c\ end} = 0.67$, in combination with length of growth stages published for citrus in FAO-56 which are 60, 90, 120 and 95 days for

initial, development, mid-season and late stages, respectively, from June to May. For orchards with leaf area index below $3.0 \text{ m}^2 \text{ m}^{-2}$, these K_c values can be adjusted to account for actual vegetation using site-specific measurements of effective fractional canopy cover. Single crop-specific modelling approaches proposed in this study for pecans and macadamias can be used as tools to improve water resource management through more accurate estimates of monthly and seasonal crop ET. However, more validation studies should be conducted under a range of climates, orchard ages and management practices to evaluate their applicability and identify potential areas for improvement.

CHAPTER 8: GENERAL CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

Quantification of crop water use or crop evapotranspiration (ET, composed by whole-tree transpiration – T and soil evaporation – E_s) is critical for improved irrigation scheduling and crop water use efficiency, particularly under South African climatic conditions where water scarcity and climate change are often the major causes of crop failure. This is particularly true for fruit tree crops, which are highly sensitive to both excess and shortage of water supply, thus requiring an adequate water supply for optimal fruit production and maximum orchard profitability (Garrot *et al.* 1993; Carr, 2012a). As these are important cash crops, which contribute to the growth of the South African economy, ensuring their optimum productivity is extremely important. Pecan and macadamia tree species are typical examples of these crops in South Africa. The area of cultivation and productivity of these crops have considerably increased in the country lately, with the consequence that South Africa has become the leading exporter of macadamias and the fourth largest exporter of pecans in the world (NAMC and DAFF, 2013; INC, 2015b). The rapid expansion of these industries coincides with an increased water demand for irrigation purposes and, as a result, the government has urged South African growers to increase management and efficiency of water use, for improved crop productivity with limited water supply. This can be achieved through appropriate quantification of crop water needs, and furthermore, growers and governmental institutions can have more appropriate planning for future water applications to better cope with the effects of climate change and variability. Since the ET of fruit tree crops is highly variable under various climates and orchard management practices, accurate estimates under a range of conditions, within a limited time and cost, are only possible through crop modelling. The selection of an appropriate modelling procedure, in turn, requires an understanding of the process of crop water use in relation to its main drivers.

Tree nut crops, like stone and pome fruit tree species, present a number of distinct characteristics including differences in their growth habit, being grouped as deciduous species like pecans or evergreen species like macadamias. This has resulted in

distinct climatic adaptations between the two groups, which are often associated with differences in their morphological, physiological and anatomical characteristics, which may have an impact on how T responds to environmental variability (Arora *et al.* 1992; Vilagrosa *et al.* 2012). To date, research has mostly focused on environmental regulation of T of evergreen fruit tree species such as citrus, olives and macadamias, while deciduous species have received very little attention with the existing research conducted predominantly on apples (Pretorius and Wand, 2003; Gruia *et al.* 2011). The few detailed studies that are available for both groups were mainly conducted on selected leaves, for a limited number of days and under controlled environmental conditions, which may not be entirely representative of field conditions. In addition, these studies have mostly focused on evaluating the effect of an environmental variable on T , at different levels of another variable, which is an approach that does not provide a complete picture of possible causal relationships between variables, thus limiting the establishment of thresholds of dependant variables, above which stomata exert control over T . In an attempt to fill the knowledge gaps in the scientific literature, this study conducted whole-tree sap flow studies in commercial pecan and macadamia orchards for two to three consecutive seasons using the heat ratio method. The data was subsequently used to analyse the dependency of T on changes in environmental variables using a quantile regression approach that provides a more complete view of possible causal relationships between variables. Whole-tree T , normalised for canopy size (T_c), was well-coupled to the atmosphere in both pecans and macadamias, and was primarily driven by vapour pressure deficit (VPD), with T_c rates of both crops decreasing considerably once a threshold VPD had been reached (1.4 kPa for pecans and 1.2 kPa for macadamias), indicating a strategy for restricting water loss from the tree during these periods. Whilst, pecans and macadamias exhibited some similarities in their water use strategy, they also possessed slightly distinct mechanisms of crop water use, with T_c of the pecans being generally demand-limited (particularly at relatively lower levels of VPD), as opposed to supply-limited in macadamias (under the whole range of VPD studied). These slightly distinct crop water use patterns are likely related to their varying growth habits. Evergreen species, like macadamias, tend to be more conservative with respect to water use than deciduous species like pecans, because they need to tolerate severe water stress during the dry winter season, which deciduous species avoid. In addition, the presence of morphological and physiological attributes, which favour drought tolerance through water conservation mechanisms

within the tree, are more evident in evergreen species as compared to deciduous species. The common presence of a water-saving strategy in both crops, on the other hand, is typically associated to strong T_c coupling to the atmosphere in tall deciduous and evergreen perennial tree crops, where T_c is strongly regulated by the stomata.

The evidence of stomatal control of T_c in tall, deciduous and evergreen horticultural crops may be the main reason why a number of T models for these crops are typically based on a canopy conductance approach (Lloyd, 1991; Villalobos *et al.* 2000; Orgaz *et al.* 2007; Egea *et al.* 2011; Villalobos *et al.* 2013). Such models are either crop-specific (Lloyd, 1991; Orgaz *et al.* 2007), relatively too complex involving parametric variables which are difficult to obtain (Villalobos *et al.* 2000) or applied at the leaf level which may not be able to provide accurate estimations of T for an entire canopy (Egea *et al.* 2011). The only generic T model applied at the canopy level was successfully parameterized for a range of fruit tree species in one study conducted under Mediterranean conditions, but it was never validated and did not include pecans or macadamias (Villalobos *et al.* 2013). In this model, T was estimated using modelled fraction of intercepted photosynthetically active radiation (f_{IPAR}) and fairly good model parameterization results were obtained. The model used to estimate f_{IPAR} was originally developed for olive trees, which differ in tree architecture compared to a number of other fruit tree species, causing possible inaccuracy in modelling predictions. While there is only one study reporting the use of this canopy conductance model to estimate daily T of selected fruit trees, a number of studies have documented the applicability of the FAO-56 dual crop coefficient model for estimating T . The use of the latter model has raised concerns for accurate predictions of daily T of fruit tree species because evidence suggests strong stomatal control over T on these species, especially under conditions of high atmospheric demand, which means a non-linear relationship between T and ET_o (Nicolás *et al.* 2008; Rousseaux *et al.* 2009; Marin and Angelocci, 2011; Taylor *et al.* 2015). For this reason, this study compared the performance of these two modelling approaches using the same data sets. In both modelling approaches, T was estimated using f_{IPAR} estimates with a generic PAR interception model developed for fruit trees, which had not been tested for pecans and macadamias. In addition, this model did not include changes in canopy porosity in mature deciduous trees as a result of leaf senescence at the end of the season. The f_{IPAR} model was therefore improved in this study by including canopy porosity

estimates for mature trees using a thermal time approach and successfully validated it to simulate hourly and daily f_{IPAR} of pecans and macadamias planted in different field configurations. Both T models, the FAO-56 dual crop coefficient and the canopy conductance model, provided adequate estimates of T for pecans and macadamias on a seasonal basis, but diverged in their performance for daily estimates of T for both crops. Poor performance of the FAO-56 model was obtained for both model parameterization and validation, which was mainly attributable to high variability of leaf resistance throughout the growing season. This could not be accounted for in the modelling procedure using only two average values of the leaf resistance parameter (one for the initial to midseason stages and another for the end-season stage) to estimate daily T for the entire growing season. The canopy conductance model, on the other hand, showed adequate performance during model parameterization and validation for both pecans and macadamias, which was mainly attributable to the model's accountability in predicting decreased T rates with increased VPD that is a very typical characteristic of well-coupled, tall horticultural crops in which T is strongly regulated by the stomata. Its good performance was, however, very dependent on appropriate estimates of daily f_{IPAR} and determination of accurate crop parameters for each tree species, regardless of the difference in their type of growth habit. This model can therefore potentially assist growers to schedule their irrigation more appropriately and identify options for water savings through the use of more efficient irrigation systems and strategies that help minimize E_s .

Soil evaporation is a major component of crop ET, especially in orchard crops, where it can be above 40% of the total crop ET (Bonachela *et al.* 2001). Therefore, E_s should be assessed in order to develop feasible management practices for storing and conserving water within the soil profile, or to identify more efficient irrigation systems with reduced or negligible E_s . This can be achieved with the help of E_s models. The identification of a mechanistic E_s model that represents realistic conditions of E_s variability would require an understanding of the process in relation to the main drivers. This study provided first time insights into the variability of E_s beneath the canopy of pecan and macadamia trees cultivated on different soil types and in different planting configurations, with distinct orchard irrigation and pruning practices. Changes in E_s were assessed through field measurements using micro-lysimeters and E_s modelling with a successfully parameterized and validated FAO-56 dual crop coefficient model.

The variability of E_s was practically independent of the growth habit of the crop. Spatial changes in E_s and model sensitivity were strongly dependent on fluctuations of canopy cover (particularly for closed-canopy orchards) and fraction of the soil surface wetted by irrigation (mainly in open-canopy orchards). Temporal changes in E_s , on the other hand, were strongly influenced by fluctuations in the atmospheric evaporative demand. Total seasonal E_s was the highest in the young, drip irrigated pecan orchard, with 60% soil surface covered by grass (70 – 80% of the crop ET), followed by the young, drip irrigated macadamia orchard with 25% soil surface covered by grass (43 – 45% of the crop ET), and the lowest in the mature, micro-sprinkler irrigated pecan orchard, with a bare soil surface (6 – 18% of the crop ET). Mulch application on the area wetted by irrigation considerably decreased total seasonal E_s in young pecan and macadamia orchards (23 – 42%) particularly under high frequency irrigation, but had very little impact on the mature, close-canopy pecan orchard. The high variability of E_s and T suggests that these components of crop ET should be modelled separately for more accurate predictions of daily crop water use, which can significantly contribute to improved irrigation scheduling. However, for irrigation planning purposes, in which longer time-step modelling, such as monthly and seasonal basis, is usually sufficient for accurate predictions, simple approaches that model crop ET as a whole would perhaps be more appropriate and easily adopted by the grower, due to their user-friendliness and requirement of fewer input parameters for implementation.

A number of simple, empirical modelling procedures, based on the single crop coefficient approach, have been developed to estimate monthly and seasonal crop ET of pecans in arid climatic regions of New Mexico, USA, where pecan orchards are mainly flood irrigated (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). Unfortunately, none of these empirical modelling approaches have been evaluated in production regions other than where they were developed, which differ in both the climate and irrigation system employed. While a number of models have been developed for pecans, there are currently no modelling approaches that have been developed to estimate ET of macadamias (Carr, 2012a). For these reasons, this study focused on generating additional knowledge on pecan and macadamia water use, through quantification of crop ET throughout the season in relation to its main drivers, under varying weather conditions and orchard management practices. Single generic

crop coefficient approaches from FAO-56 were evaluated to estimate crop ET of pecans and macadamias, and their performance compared against new, single crop-specific modelling procedures. Monthly crop coefficients and crop ET values of mature pecans were highly variable throughout the season (0.6 – 1.4 and 60 – 160 mm) and from one season to another (944 – 1035 mm), being strongly influenced by changes in canopy cover. A similar trend was not evident in young evergreen macadamia trees, where there were no dramatic changes in canopy size for the majority of the growing season, resulting in fairly constant crop coefficients (0.62 – 0.77), monthly crop ET totals (52 – 87 mm), as well as seasonal crop ET (821 – 846 mm). The most accurate predictions of monthly crop ET of pecans were obtained with an improved crop-specific single crop coefficient model, which adjusts the reference crop coefficient curve for pecans to specific climatic conditions based on observations of canopy growth and development for various growth stages within the season, following a six stage crop growth curve approach. Monthly crop ET of macadamias, having a leaf area index above $3.0 \text{ m}^2 \text{ m}^{-2}$, on the other hand, was accurately predicted with the generic FAO-56 single crop coefficient approach using macadamia-specific time-average K_c values ($K_{c \text{ ini}} = 0.71$, $K_{c \text{ mid}} = 0.72$ and $K_{c \text{ end}} = 0.67$, in combination with the following length of growth stages: 60, 90, 120 and 95 days for initial, development, mid-season and late stages, respectively, from June to May). These findings suggest that the K_c curve, including the magnitude and variability of K_c values in tree nut crops, is a crop-specific characteristic. As a result, generic mechanistic modelling procedures should be parameterized for each crop species, while simple empirical approaches should be developed specifically for each crop in order to predict the water use of these crops more accurately. The latter is particularly important for deciduous species, due to dramatic changes in canopy growth during the season, which causes the crop water use dynamics to be more complicated.

8.2 RECOMMENDATIONS FOR FUTURE RESEARCH

This study measured the water use of pecans and macadamias in three experimental orchards (two pecan orchards located in a semi-arid, subtropical area and one macadamia orchard situated in a humid, subtropical area) and the data was subsequently used to parameterize and validate models of T , E_s and crop ET using

independent data sets of field measurements. These models can be excellent tools to help quantify water use of pecan and macadamia orchards under a range of climates and orchard management practices. However, more validation studies should be conducted in different climatic areas, soil types, orchard ages and management practices to provide qualitative and quantitative insight on the models' potential to predict outcomes under conditions differing from those used to parameterize the models. This type of model evaluation can also assist in model improvement.

The canopy conductance model should be further validated to assess whether the crop-specific parameters **a** and **b** retain their accuracy under a range of orchard ages and climates. Additional validation studies should also be conducted for the simple, single crop-specific modelling procedures proposed in this study to predict monthly and seasonal crop ET of pecans and macadamias. These models were successfully validated in this study for large canopy orchards with seasonal average leaf area index above $3.0 \text{ m}^2 \text{ m}^{-2}$. Therefore, it is important that model predictions be also tested against actual measurements in young orchards with leaf area index equal or below $3.0 \text{ m}^2 \text{ m}^{-2}$. This will assess whether the reference K_c values derived for a mature pecan orchard in New Mexico or time-averaged K_c values determined for a macadamia orchard with leaf area index above $3.0 \text{ m}^2 \text{ m}^{-2}$ can be adequately adjusted to much smaller amounts of actual vegetation in young orchards using measurements of canopy cover.

In the FAO-56 dual crop coefficient model of E_s , longer periods of E_s measurements should be done for each cycle to assess complete reduction cycles in order to have better observations of the falling rate stage of E_s that occurs in proportion to the amount of water remaining in the topsoil layer. This is particularly important for the sandy loam soil, where such observations were impossible to make in the study orchard due to the high frequency of drip irrigation events which constantly refilled the topsoil layer back to field capacity.

The environmental regulation of T of pecans and macadamias investigated in this study revealed the presence of a strong stomatal control of T in these tree nut species. Further research should however be conducted to identify specific locations of resistances to water flow within the tree under non-limited soil water supply conditions.

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