

REPORT TO THE WATER RESEARCH COMMISSION
and
DEPARTMENT OF AGRICULTURE, FORESTRY & FISHERIES



agriculture,
forestry & fisheries

Department:
Agriculture, Forestry and Fisheries
REPUBLIC OF SOUTH AFRICA

**The water use of selected fruit tree orchards
(Volume 1): Review of available knowledge**

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WRC REPORT NO. 1770/1/14
ISBN 978-1-4312-0574-5

JULY 2014

Obtainable from

Water Research Commission
Private Bag X03
Gezina, 0031

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This report forms part of a series of two reports. The other report in the series is *The water use of selected fruit tree orchards (Volume 2) Technical report on measurements and modelling* (WRC Report No. 1770/2/14).

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EXECUTIVE SUMMARY

Motivation

South Africa faces a number of water resource challenges common to other dry countries. These include the realities of increasing water scarcity and competition for water due to population expansion, economic growth and climate change. There is an urgent need to improve water productivity and to reduce non-beneficial use of water particularly in the agricultural sector where, for example, irrigated agriculture uses approximately 60% of the available surface water resources. As a result of generally low and erratic rainfall and the high value of fruit crops, almost all fruit production in South Africa is under irrigation. It is not surprising, therefore, that the need to improve knowledge on irrigation scheduling and water use efficiency of fruit tree crops in both the summer and winter rainfall areas of South Africa where water stress is increasing, has been identified. A goal of modern agriculture (fruit tree orchards in particular) is to use less water for irrigation without a decrease in fruit quality and yield. More specifically, there is evidence from literature that soil-based water balance measurements present a challenge when trying to obtain accurate and reliable information on water use. Due to these uncertainties it is well known that there is a tendency for farmers to over-irrigate. Measurements of transpiration (sap flow) and total evaporation are useful in validating and improving water-use models for fruit tree orchards. This, in turn, can improve the accuracy of irrigation scheduling for these crops and, ultimately, ensure wiser use of water in this sector. This is particularly important for the fruit tree industry where at least 90% of production is dependent on irrigation. More direct observations on the water use of fruit tree orchards is required to improve management advice to farmers for drawing up on-farm water management plans for fruit production, and towards increasingly efficient and productive water use within the fruit tree industry.

Technological advances in sap flow and energy balance monitoring instrumentation, together with available expertise in the utilisation of these techniques makes accurate measurements of transpiration and total evaporation possible. Through the use of these techniques, accurate measurements of the water actually used by fruit trees, together with additional site-specific information on climate, soil and tree physiological / phenological changes, can provide data that is useful for water management, modelling and regulation within the industry. These were the primary motivators behind the initiation of this solicited project by the Water Research Commission, who provided funding together with the Department Agriculture, Forestry & Fisheries. The project was led by the CSIR (Natural Resources

and Environment), in close collaboration with the University of Pretoria (Dept. Plant Production & Soil Science) and Citrus Research International (CRI). The project was undertaken over 7 years, between April 2007 and March 2014.

Project Objective and Aims

The overall objective of this project was to develop comprehensive knowledge of water use characteristics and the actual water use of selected fruit tree/orchard crops for application in fruit tree/orchard management in South Africa.

The specific aims of this project were:

1. To identify and review available knowledge on water use of tropical, sub-tropical and deciduous fruit trees/orchard crops in South Africa
2. To assess, rank and select the most important fruit trees/orchard crops in South Africa
3. To measure the unstressed water use and ancillary variables of at least 4 types of fruit tree/orchard crops at selected sites to enable modeling using available South African or international models. The selection should be representative of sub-tropical and deciduous fruit trees/orchard crops in winter and summer rainfall areas.
4. To develop, verify and validate the most appropriate crop water use model(s) for the selected fruit trees/orchard crops.

Methods

The first task was a comprehensive review of the current state of knowledge regarding the water use of deciduous, tropical and sub-tropical fruit tree orchards (Volume 1 of this report). Further objectives of the review were to use the above information to a) provide an overview of the fruit tree / orchard industry in South Africa (economic importance, distribution and extent), b) assess and define the most commonly applied management practices (orchard layout, fruit types / cultivars being used, irrigation practices), and c) evaluate hydrological aspects (soil types, irrigation water use, available data sets / confidence in water use measurements, and water use measurement methodologies and models available). It should be noted that the Terms of Reference of this project specified that the Knowledge Review should be undertaken at the commencement of the project, followed by the prioritisation exercise. Consequently, much of the information contained in the review is pre-2007 when the project commenced. Following this review it was possible to prioritise fruit tree species in terms of a) their economic importance, b) extent of planted area, c) geographic distribution and d) gaps in knowledge on water use / irrigation scheduling. The second task was a workshop with

prominent members of the fruit tree / orchard industry. The aims of this workshop were to a) inform relevant stakeholders of the objectives and methodology of this project; b) obtain approval regarding the selection of the fruit tree / orchard crops for water use measurement and the proposed sites for monitoring (given the constraints of the project); and c) build networks and foster collaboration with stakeholders in order to effectively transfer knowledge and ensure the applicability of the research.

The selection of which fruit tree species to measure, and where, was guided by the industry review (species prioritisation study) together with the terms of reference of the project (measure at least 4 fruit tree / orchard crop species covering both the winter and summer rainfall regions of the country). The selection process was also aided by the above workshop with members of the fruit tree / orchard industry, where recommendations on appropriate sites, species and cultivars were made. Additional monitoring site selection aspects considered suitability for applying the Heat Pulse Velocity (HPV) and/or Eddy Covariance techniques. Aspects such as security, ease of access, and the cooperation of landowners were also considered. Sites at agricultural colleges or with farmers applying best-management practices were utilised as they were preferable in terms of security and adherence to more stringent levels of orchard management, fruit quality, irrigation management, fertilisation etc. Mature, unstressed trees were selected to ensure that peak water use rates were measured, and the sites were deemed to be representative of the species being measured. The trees at all sites were irrigated and managed for optimum fruit quality production. Potential target species included deciduous crops such as pome fruit (pears and apples), stone fruit (peaches, plums and nectarines) and nut species (pecans), as well as sub-tropical species such as macadamia, avocado and citrus trees.

The following species and sites were eventually selected for measurements and modelling (Volume 2 of this report):

- A deciduous winter-rainfall pome-fruit species ('Cripps' Pink' apples at Ceres, Western Cape Province),
- A deciduous winter-rainfall stone-fruit species 'Alpine' nectarines at Wolseley, Western Cape Province),
- An evergreen winter-rainfall citrus site ('Rustenburg' Navel oranges at Citrusdal, Western Cape Province)
- Two evergreen summer-rainfall citrus sites ('Delta' Valencia and 'Bahaininha' Navel oranges at Groblersdal, Limpopo Province; 'Midnight' Valencia oranges at Malelane, Mpumalanga Province),
- Two deciduous summer-rainfall stone-fruit species ('Alpine' nectarines and 'Transvalia' peaches at Rustenburg, North-West Province).

- A deciduous summer-rainfall nut species ('Choctaw' Pecans, at Cullinan, Gauteng),
- An evergreen summer-rainfall subtropical nut species ('Beaumont' Macadamias at White River, Mpumalanga Province).

At least three trees (and up to 6) were monitored for sap flow rates at each site to account for variation in individual tree water use rates. Micrometeorological techniques (e.g. eddy covariance and surface renewal) were used for orchard scale monitoring of total evaporation at the sites. Irrigation timing and amounts were determined from metered records at the sites, or from direct measurements on the irrigation lines. This comprehensive sampling strategy ensured that the variables required for later modelling efforts were collected.

In terms of ET measurements the micrometeorological techniques were deployed for "window periods" (1-2 week period in different seasons) to obtain total evaporation measurements (transpiration and evaporation from the soil), while the Heat Ratio Method (HRM) of the Heat Pulse Velocity (HPV) technique was deployed continually (hourly measurements) to account for daily and seasonal variation in transpiration for up to three years. Following a minimum period of 1 growing season of field monitoring at each site the selected total evaporation and / or water balance model(s) (identified in the draft model report) were tested, modified where necessary, calibrated and verified using the observed data collected at the site. Efforts were made to quantify the crucial variables that influence water use, and to qualify how they exert that influence through a combination of observed data analysis and modelling. The ultimate objective of the modelling exercise was to produce sets of crop coefficients (K_c and K_{cb}) for each fruit tree species sampled, and to recommend the most appropriate model or modelling approach.

Results

The primary outputs generated by the project included:

- review of the fruit tree industry in South Africa, with respect to economic importance, geographic distribution, extent of planted area, irrigation / management practices, and information on water use (data and models),
- quantitative water use information in the form of hourly, daily, monthly, seasonal and annual transpiration volumes for the range of fruit tree species and cultivars that were monitored,
- seasonal observations of hourly and daily total evaporation (orchard) water use volumes for the range of fruit tree species and cultivars that were monitored,

- seasonal observations of daily soil evaporation rates at a range of measurement sites,
- detailed (hourly) supporting data sets of weather, soil water and irrigation, together with seasonal / annual variation in tree attributes.
- information on the suitability, input requirements and effectiveness of models for predicting the water use of the range of fruit tree species / cultivars tested,
- monthly basal and full crop coefficients, derived from measurements and modelling, for the respective fruit tree species / cultivars that were monitored,
- technology transfer actions in the form of presentations, publications and farmer information days,
- capacity building through student training, higher degrees and technical project experience.

Conclusions

An early deliverable in this project reviewed all aspects of the fruit tree and orchard crop industry in South Africa that could potentially influence the extent and variability of its overall water use impacts. One of the findings that emerged from this review was the tremendous diversity of species, cultivars, and bio-physical growing conditions (climate, soils and management practices) that exist when considering the entirety of the industry. The review provided the information necessary to assess, rank and select the most important fruit tree species to focus attention on for measurement and modelling. This formed the basis of subsequent project decisions on *which* species to measure, *where* to measure them, *what* to monitor, and *how* to model them.

The quantitative and modelled water use results from the project have reflected the diversity of the fruit tree industry. The collected data has demonstrated the influence of growth forms, phenological stages, climatic conditions, irrigation and management practices on overall water use patterns and volumes. This has improved available knowledge of water use characteristics and the actual volumetric water use of the range of fruit tree crops monitored in this project. It is anticipated that the information will assist in future fruit tree/orchard irrigation scheduling, on-farm water management and water allocation decisions in South Africa, and thereby promote increased water-use efficiency, water productivity and water security in the country.

Extent to which contract objectives have been met

The terms of reference for this project required “*the measurement of the unstressed water use and ancillary variables of at least 4 types of fruit tree/orchard crops at selected sites to enable modeling using available South African or international models.*” Furthermore, the conditions stipulated that “*the selection should be representative of sub-tropical and deciduous fruit trees/orchard crops in winter and summer rainfall areas.*” Consequently, the decisions of 1) what species to measure, and 2) where to measure them, needed to ensure that the fruit tree / orchard species and cultivars that were eventually selected met the following criteria:

- They consisted of at least 4 different species or cultivars,
- They included both subtropical and deciduous species,
- The monitoring sites were located in both summer, and winter rainfall regions respectively.

A ranking procedure was developed to characterize individual crops into the required categories and this was used in the decision making process. The subsequent monitoring of Valencia and navel oranges, apples, nectarines, peaches, pecans, and macadamias ensured that the chosen species / cultivars covered summer and winter rainfall zones, evergreen, deciduous and subtropical crops, that included both fruits and nuts. The successful monitoring of this wide range of fruit tree species and cultivars therefore exceeded the minimum requirements for the project. Project activities moved from an initial planning, review and “desktop-type” stage to a field measurement and modelling phase. Intensive measurements of a range of relevant variables at the various sites were conducted, modelling exercises were undertaken at the respective sites once sufficient field data had been collected, and findings from the respective tasks described above were consolidated.

The range and extent of the project was ambitious, with monitoring sites across South Africa. The composition of the multi-disciplinary and well-distributed project team ensured the collection and comparison of fruit tree water use data from a wide range of climatic zones and species / cultivars. This has yielded a unique and extensive data set that provides comprehensive knowledge of water use characteristics and the actual water use of selected fruit tree/orchard crops under South African conditions.

ACKNOWLEDGEMENTS

The research reported on here formed part of a project initiated, funded and managed by the Water Research Commission (WRC, 2008), with additional funding from the Department Agriculture, Forestry and Fisheries. Their support is gratefully acknowledged. We also wish to sincerely thank the following members of the project reference group for their contributions and guidance:

Dr GR Backeberg	Water Research Commission (Chairman)
Mr AS Roux	Department of Agriculture (Western Cape)
Mr LP Reynolds	DuToitAgri
Dr E Lötze	Stellenbosch University
Mr C Malan	Netafim
Ms A Zeelie	Agricultural Consultants International
Ms MJ Gabriel	Department of Agriculture, Forestry & Fisheries
Dr P Myburgh	Agricultural Research Council
Dr T Volschenk	Agricultural Research Council
Dr HF le Roux	Citrus Research International
Mr JT Vahrmeijer	Citrus Research International
Mr D Alberts	Private Practice
Dr H Pienaar	CSIR

TABLE OF CONTENTS

Executive Summary	iii
Acknowledgements	ix
Table of Contents	xi
List of Tables	xiii
List of Figures	xv
List of Symbols and Abbreviations	xvii
1 Knowledge review	1
1.1 Introduction and background	1
1.2 Definitions of deciduous, tropical and sub-tropical fruit trees and orchard crops	3
1.2.1 <i>Deciduous species</i>	3
1.2.2 <i>Tropical and subtropical species</i>	4
1.3 Distribution of fruit trees and orchard crops in South Africa	5
1.3.1 <i>Winter rainfall region</i>	8
1.3.2 <i>Summer rainfall region</i>	10
1.3.3 <i>Year-round rainfall region</i>	13
1.4 Orchard layout	14
1.4.1 <i>Deciduous species</i>	15
1.4.2 <i>Tropical and subtropical species</i>	16
1.5 Fruit types / cultivars grown in South Africa and their relative importance	27
1.5.1 <i>Deciduous species</i>	27
1.5.2 <i>Tropical and subtropical species</i>	34
1.6 Soil types suitable for fruit tree orchards	37
1.6.1 <i>Deciduous species</i>	38
1.6.2 <i>Tropical and subtropical species</i>	39
1.7 Irrigation practices	42
1.7.1 <i>Scheduling</i>	43
1.7.2 <i>Types of irrigation</i>	57
1.7.3 <i>Irrigation strategies</i>	58
1.8 Appropriate water use measurement methodologies	63

1.8.1	<i>Soil water balance method</i>	63
1.8.2	<i>Micrometeorological methods</i>	65
1.8.3	<i>Soil evaporation and transpiration combination method</i>	67
1.9	Water use information.....	70
1.9.1	<i>Water use of deciduous fruit tree species</i>	75
1.9.2	<i>Water use of subtropical fruit tree species</i>	78
1.10	Appropriate models.....	82
1.10.1	<i>Soil water balance model (SWB)</i>	82
1.10.2	<i>MAESTRA model</i>	83
1.10.3	<i>FAO-56 model</i>	84
1.10.4	<i>Penman-Monteith model</i>	85
1.11	Conclusions	87
	References	88
	Appendix A: Heat pulse velocity Sap-Flow monitoring system	106
	Appendix B: Energy balance methods for measuring total evaporation.....	119

LIST OF TABLES

Table 1: Total fruit production in South Africa in 2005/2006 (DAFF, 2007).....	7
Table 2. Guidelines for planting distances (m) for different crops (rootstocks, soils and climate must be taken into account and management strategies adapted accordingly) (Stassen and Davies 1996).	17
Table 3. Recommended tree spacing for the hot/very hot areas of South Africa (Outspan, 1997).....	21
Table 4. Recommended tree spacing for the intermediate areas of South Africa (Outspan, 1997).....	22
Table 5. Recommended tree spacing for the cool areas of South Africa (Outspan, 1997).....	23
Table 6. Recommended tree spacing for the cold areas of South Africa (Outspan, 1997).....	24
Table 7. Area planted per grape cultivar in South Africa in 2006 (DFPT 2006).	28
Table 8. Area planted per apple cultivar in South Africa in 2006 (DFPT 2006).	29
Table 9. Area planted per pear cultivar in South Africa in 2006 (DFPT 2006).	29
Table 10. Area planted per dessert peach cultivar in South Africa in 2006 (DFPT Tree Census 2006).....	30
Table 11. Area planted per cling peach cultivar in South Africa in 2006 (DFPT Tree Census 2006).	31
Table 12. Area planted per apricot cultivar in South Africa in 2006 (DFPT Tree Census 2006).	31
Table 13. Area planted per plum cultivar in South Africa in 2006 (DFPT Tree Census 2006).	32
Table 14. Area planted per nectarine cultivar in South Africa in 2006 (DFPT Tree Census 2006).	33
Table 15. Area planted per prune cultivar in South Africa in 2006 (DFPT Tree Census 2006).	33
Table 16. Area planted per Citrus type in South Africa in 2006 (CGA 2006).	35

Table 17. A summary of the main classes of irrigation scheduling approaches, including their main advantages and disadvantages (Jones 2004).....	46
Table 18. Ranges in available water capacity and intake rate for various soil textures (Tan 2007).....	56
Table 19. Irrigation depths for various crops (Tan 2007).	57
Table 20. A summary of measured water-use rates across a range of fruit tree species, from published literature.	72
Table 21. Monthly water use of mature ‘O’Henry’ peaches measured with a weighing lysimeter (L) and calculated (C) using a three-segment linear model based on the lysimeter data (Ayars et al., 2003).....	75
Table 22. Evaporation and crop coefficient data for a developing citrus orchard with a grass cover in Florida (adapted from Rogers et al., 1983 and Consoli et al., 2006).	79
Table 23. Average mean daily reference total evaporation (ET_o), observed crop coefficients (K_{co}) and crop total evaporation (ET_c) for fully mature, clean-cultivated, microsprinkler-irrigated navel orchard in California for 2003 and 2004 (Snyder and O’Connell, 2006).....	81

LIST OF FIGURES

Figure 1: Seasonal rainfall distribution in South Africa (Schulze and Maharaj, 2006).....	6
Figure 2: Pome production areas in South Africa (DFPT 2007).....	9
Figure 3: Stone fruit production areas in South Africa (DFPT 2007).....	9
Figure 4: Table grape producing regions in South Africa (DFPT 2007).	10
Figure 5. Distribution of tropical fruit growing areas in South Africa (Source: www.places.co.za/maps/south_africa_map.gif).	11
Figure 6. Distribution of subtropical fruit growing areas in South Africa (Source: http://home.global.co.za/~mercon/samap.gif).....	12
Figure 7. Distribution of fruit growing areas in South Africa according to generalized soil types (ISCW-ARC). The abbreviations of the soil types are: Ferralsols (FR), Acrisols (AC), Cambisols (CM), Plinthosols1 (PT1), Plinthosols2 (PT2), Luvisols1 Luvisols1 (LV1), Luvisols2 (LV2), Vertisols (VR), Phaezems/Kastanozems (PH/KS), Nitisols (NT), Leptosols1 (LP1), Leptosols2 (LP2), Fluvisols (FL), Arenosols1 (AR1), Arenosols2 (AR2), Arenosols3 (AR3), Solonchaks (SC), Podzols (PZ), Regosols (R). (from http://www.esri.com/mapmuseum/mapbook_gallery/volume19/agriculture3.html).....	38
Figure 8. Classification of irrigation scheduling models and methods used in South Africa (Stevens 2007).	49
Figure 9. The implementation of different irrigation scheduling methods by farmers surveyed by Stevens (2007). Recorded figures from the survey and reported figures by representative respondent, supported by consensus of a smaller reference group are shown (Stevens, 2007).	50
Figure 10. Periods of low, moderate and high water demand by an avocado tree for the various growth processes throughout the year in the Southern Hemisphere (Whiley et al., 1988a).....	60
Figure 11. Average monthly water consumption of different sized citrus trees (Outspan 1997).	61
Figure 12. Components of the water balance equation in irrigated orchards.	64

Figure 13. Illustration of different probe set insertion depths applied in the Heat Pulse Velocity technique.	69
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LIST OF SYMBOLS AND ABBREVIATIONS

Roman Symbols

c_p	specific heat capacity of air at constant pressure (approximately $1040 \text{ J kg}^{-1} \text{ K}^{-1}$)
D	deep drainage (mm)
E_s	soil evaporation (mm day^{-1})
ET	total evaporation (mm)
ET_o	FAO-56 Reference Total Evaporation (mm)
ET_{sz}	ASCE-EWRI short grass (0.12 m) reference evaporation (mm)
g_c	canopy conductance (m s^{-1}) = $(1/r_s)$
g_{cmax}	maximum conductance (m s^{-1})
G	soil heat flux (W m^{-2})
H	sensible heat flux (W m^{-2})
I	irrigation (mm)
K_c	crop coefficient (based on total evaporation)
K_e	soil evaporation crop coefficient
K_{cb}	basal crop coefficient (based on transpiration)
LE	latent heat flux (W m^{-2})
P	precipitation (mm)
Q	streamflow (mm)
r_b	leaf boundary layer resistance (s m^{-1})
r_s	stomatal resistance (s m^{-1})
R	surface runoff (mm)
R_n	net irradiance (W m^{-2})
$spha$	stems per hectare
T	transpiration (mm or L)
T_a	temperature of the air ($^{\circ}\text{C}$)
T_{sonic}	air temperature using sonic temperature ($^{\circ}\text{C}$)
V_h	Heat Pulse Velocity (cm hr^{-1})
w	vertical wind velocity (m s^{-1})
W	contribution from water table upward (mm)

Greek symbols

Δ	slope of saturated vapour pressure vs air ($\text{kPa } ^{\circ}\text{C}^{-1}$)
ΔS	change in soil water storage (mm)
γ	psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$)
θ	actual volumetric water content ($\text{m}^3 \text{ m}^{-3}$)
ρ_a	density of air (approximately 1.12 kg m^{-3})
ρ_s	bulk density of soil (kg m^{-3})

ρ_w	density of water (kg m^{-3})
λ	latent heat of vaporisation of water (J kg^{-1})

Abbreviations

ASCE	American Society of Civil engineers
AWS	Automatic weather station
CGA	Citrus Growers Association
CRI	Citrus Research International
CSIR	Council for Scientific and Industrial Research
DAFF / DOA	Department of Agriculture, Forestry and Fisheries
DFPT	Deciduous Fruit Producers Trust (now HortGro Science)
DWAF/ DWA	Department of Water Affairs
FAO-56	Food and Agriculture Organisation, paper no. 56
GDP	Gross Domestic Product
HPV	Heat Pulse Velocity
HRM	Heat Ratio Method
LAI	Leaf Area Index
MAP	Mean Annual Precipitation
MDS	Maximum Daily Shrinkage
PAR	Photosynthetically Active Radiation
PAW	Plant Available Water
PRD	Partial Root-zone Drying
RDI	Regulated Deficit Irrigation
SAMAC	South African Macadamia Growers Association
SAMGA	South African Mango Growers Association
SANCID	South African National Committee on Irrigation and Drainage
SAPPA	South African Pecan Producers Association
SWB	Soil Water Balance
SWP	Stem Water Potential
TDR	Time Domain Reflectometry
VPD	Vapour Pressure Deficit
WUE	Water Use Efficiency

1 KNOWLEDGE REVIEW

1.1 Introduction and background

The need to improve irrigation scheduling and water use efficiency of fruit tree crops in the summer and winter rainfall areas of South Africa, where water stress is increasing, has been identified (Roux, 2006). In a previous WRC report on the optimisation of irrigation management in mango trees, Pavel *et al.* (2003) noted that the goal of modern agriculture (fruit tree orchards in particular) was to use less water for irrigation without a decrease in fruit quality and yield. This sentiment was echoed in a further WRC report on irrigation scheduling for deciduous fruit orchards by Volschenk *et al.* (2003), who noted that an alternative means of deriving crop coefficients for fruit tree crops was required. They concluded that measurements of transpiration (sap flow) would be useful in validating total evaporation (transpiration and evaporation) models for fruit tree orchards. This, in turn, would improve the accuracy of irrigation scheduling for these crops and, ultimately, ensure wiser use of water in this sector. This is particularly important for the fruit tree industry where at least 90% of production is dependent on irrigation.

According to the above reports, there is currently a lack of comprehensive information on the water use of fruit trees, and available information on water use is incomplete and unsubstantiated. As explained in the rationale for this research project, there is a need for more definitive transpiration results, in order to accurately calibrate and verify total evaporation models. More specifically it is clear that soil based (water balance) measurements present a challenge to obtain accurate and reliable information on water use. Distinction needs to be made between the transpiration / interception and soil evaporation components of total evaporation data. This is difficult with a water balance approach, and more direct observations of transpiration are required. Correct knowledge is absolutely essential for drawing up on-farm water management plans for fruit production. Furthermore, according to the National Water Resources Strategy of 2004, measures will be taken to increase the efficiency of water use. These measures include registering water use to levy charges and authorising water use by issuing licences. In the case of fruit trees under irrigation, more accurate information is urgently required as a basis for water use charges and licensing. These were the primary motivators behind the initiation of this solicited project by the Water Research Commission.

Existing models in South Africa cannot confidently simulate water use of fruit trees for different climate, soil, water and management conditions. Process-

based research on the water use of fruit tree orchards is required to provide accurate site specific information. These data will facilitate the development / validation of tree-specific water use models, applicable on a wider scale. More precise modelling approaches and information on water use will, in turn, improve management advice to farmers towards the efficient and productive water use of fruit trees.

The initiation of projects such as the Agricultural Water Conservation Project that was implemented in the Western Cape (Roux, 2006), illustrate the increasing focus that is being placed on the more efficient use of this country's scarce water resources. This particular project monitored actual on-farm irrigation water use and the associated farming practices utilised by individual farmers, and then compared the amounts of water used against theoretical calculated water requirements. It is this latter aspect within which most uncertainty exists, i.e. what is the minimum amount of water that various crop species require before quantity and quality of fruit production start to be negatively affected. Obtaining accurate estimates of the water requirements of specific fruit tree and orchard species has been hampered by various factors including:

- the diversity of fruit tree and orchard crop species grown in South Africa,
- the range of cultivars grown for any one species,
- the range of bio-physical conditions (climate, soils, management choices) under which fruit trees and orchard crops are grown in South Africa,
- the shortcomings of calculating fruit tree water use as the residual of components within a soil water balance
- the requirement for specialist expertise in the use of highly technical micro-meteorological measurement techniques, and the limited numbers of suitably qualified scientists in that field.

Consequently, at the start of this project in 2007, as many aspects as possible related to the water use of fruit trees and orchard crops were considered in this review, so as to attempt to obtain an overarching picture of the industry as a whole and the most pertinent areas to focus attention on for measurement and modelling. For the specific fruit tree crops analysed in this project more detail is added in the individual chapters of Volume 2.

1.2 Definitions of deciduous, tropical and sub-tropical fruit trees and orchard crops

Rieger (2006) defines a fruit as “a perennial, edible crop where the economic product is the true botanical fruit or is derived there from”. The word perennial eliminates crops grown as annuals, e.g. tomatoes, peppers, melons, even though the harvested part is a botanical fruit. The management practices for perennial and annual crops differ markedly, with management decisions in one year having an effect on growth in the following year for perennial crops.

1.2.1 *Deciduous species*

Deciduous plants are defined as those plants that shed their leaves at the end of each growing season. Deciduous also applies to plant parts that fall off the plant. In trees this is not an indicator of taxonomic status. Deciduous fruit are also referred to as temperate fruit, referring to their area of origin in the temperate zones of the world. As a result of originating in temperate climates, with a distinct seasonal rhythm, deciduous fruit trees have good cold hardiness and require chilling for uniform bud-break and good cropping. In general, 500 to 1500 chill hours (defined as number of hours of exposure to about 7°C) are required during winter (from leaf drop in autumn until August or September (Southern Hemisphere)) when the trees are dormant. Deciduous fruit trees have reduced tree size and complexity and favour the development of growth models as they display strongly synchronised phenological events due to strong environmental signals.

Deciduous fruit can be split into a number of subgroups depending on the fruit type. These sub-groupings include pome fruit, stone fruit, berries, vines (including grapes), and nuts. A pome is a fruit with two or more seeds surrounded by a papery or cartilaginous structure, the carpel wall. This grouping includes two of the most widely produced deciduous fruits in the world, viz. apples and pears. Stone fruit have a large bony endocarp surrounding the seed and include peaches, plums, nectarines, apricots, prunes and almonds. Berries are generally borne on shrubs and include raspberry, blackberry, cranberry, blueberry and strawberry. The most important member of the vine grouping is *Vitis vinifera* or grapes and is ranked second or third (depending on year) in terms of world fruit production. Two types of grape are grown namely wine and table grapes. Kiwifruit also fall in this category. Nuts include hazelnut, walnut, pecan nut and pistachio. These constitute some of the largest orchard trees grown in the world and many require summer warmth for fruit maturation.

1.2.2 Tropical and subtropical species

Tropical and subtropical species are evergreen and they therefore have persistent leaves. Tropical fruit trees originate in the tropics between 23½°N and 23½°S and have adapted to a climate which is a-seasonal and has no winter. In this environment the average diurnal variation in temperature exceeds the annual variation in mean daily temperature. The average minimum temperature in this region is about 18°C. These species have no capacity for acclimation to cold temperatures and are killed by brief exposure to sub-zero temperatures. Subtropical crops display a moderate ability to acclimate and withstand temperatures below -1 to -2°C. The subtropical region lies between 23½ & 40° N or S latitude and has a definite seasonal pattern of temperature and day-length etc., which is of benefit to the trees. The mean temperature of the coldest month is above 13°C, but should not exceed 18°C. The mean monthly minimum of the coldest month should be above 6°C. There is, however, the possibility of some winter frost in colder locations.

Some tropical single-stemmed species are capable of growing and producing fruit constantly (e.g. banana, pineapple, oil palm and papaya). Fruiting is either concurrent with continuous growth (e.g. papaya) or continuous growth culminates in flowering (e.g. banana), but in both instances yield is enhanced in environments that are conducive to vegetative growth (Verheij 1985). Other tropical and subtropical trees are branched and there is constant trade-off between vegetative and reproductive growth, often resulting in erratic and inconsistent yields (e.g. avocado, mango, coffee, jackfruit, cacao and litchi). In this case, environments that are conducive to vegetative growth result in very poor fruiting (Verheij 1985). The trees therefore need to be manipulated in order to improve the balance between flowering and fruiting. As a result of the a-seasonal environment in the tropics there are no strong environmental cues for flowering. Branched species therefore either flower synchronously in response to weak environmental cues (e.g. a dry spell) or asynchronously. When plants grow asynchronously, each tree, sector of a tree, or individual branch, flushes, flowers and fruits in its own time (Verheij 1985). Subtropical climates provide stronger environmental cues and generally trees will grow synchronously in these environments, making management practices easier. Citrus is one of the most widely grown subtropical fruits and includes oranges, grapefruits, lemons, limes and easy-peelers (Mandarins, Clementines, Tangerines etc.). Other fruits capable of growing well in subtropical climates include avocado, litchi, mango, guava, olive, date and macadamia, among others. Fruits that can be grown outside a tropical environment, but suffer a reduction in potential yield during the winter period, include papaya, pineapple and banana. Fruits that belong in a truly tropical environment include oil palm,

durian, mangosteen, cashew nut, coffee, coconut, rambutan, longan and cherimoya.

1.3 Distribution of fruit trees and orchard crops in South Africa

One of the chief factors influencing the distribution of fruit tree/orchard species is temperature. The temperature at which optimum plant growth occurs varies with the plant and the stage of development of the plant (Janick 1986). Each species also has a maximum and minimum growth temperature, above and below which injury occurs. In this regard the mean daily minimum of the coldest month is a good indication of the suitability of a fruit tree/orchard species for a specific location (Watson and Moncur 1985). This will give an indication if temperatures will be too low so as to cause injury to the plant or will be insufficient to satisfy the chilling requirements of the crop. However, all plants will suffer chilling injury if the temperature drops too low. The temperature at which chilling injury occurs depends on the species and the stage of development. Dormant apple trees can survive temperatures far below freezing when dormant, but will be damaged by light frosts during the flowering stage.

Other climatic factors also play a crucial role in determining the distribution of fruit tree/orchard crops. Humidity and rainfall distribution play an important role in disease and pest incidence and can limit the areas in which certain crops can be grown successfully. The occurrence of wind and the incidence of solar radiation also impact upon fruit tree cultivation. In terms of rainfall, South Africa can be split into three broad regions, viz., 1) winter rainfall region, 2) summer rainfall region and 3) year-round rainfall region (Figure 1).

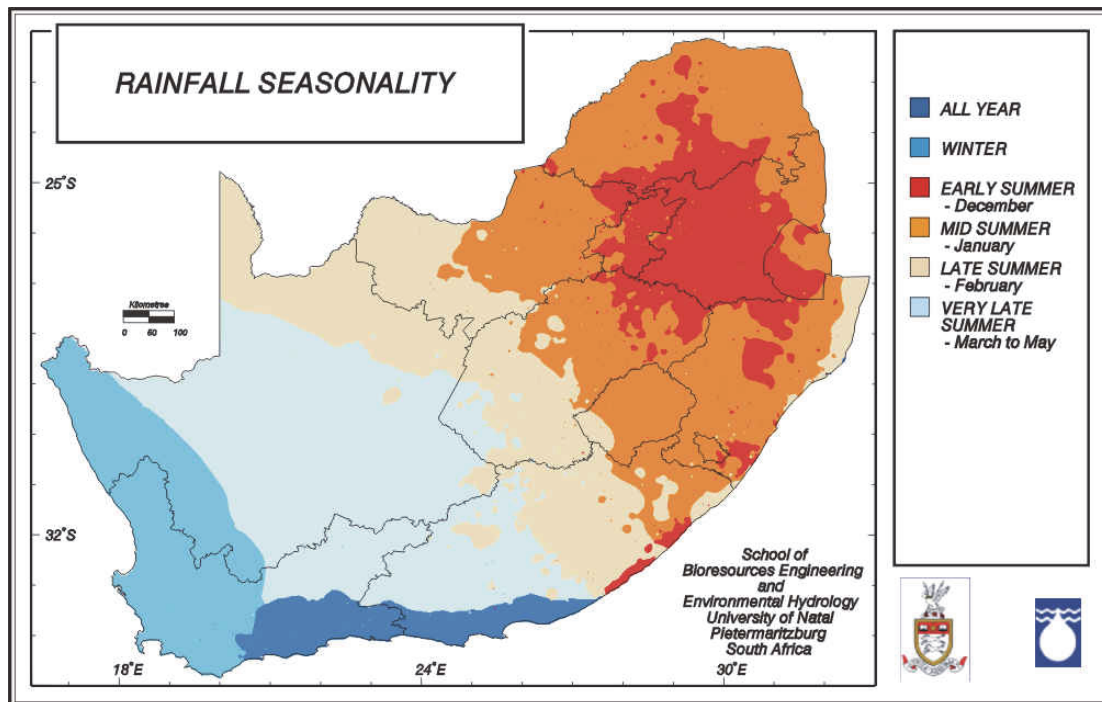


Figure 1: Seasonal rainfall distribution in South Africa (Schulze and Maharaj, 2006).

The wide range of climatic zones in South Africa lends itself to the production of a wide range of fruit. The total production of fruit and the gross value thereof for 2005/2006, according to the Directorate of Agricultural Statistics 2007, was approximately R11.3 Bn (Table 1).

Table 1: Total fruit production in South Africa in 2005/2006 (DAFF, 2007).

Fruit Crop	Total Production (t)	Total value (R '000)
Grapes	1 550 415	4 551 299
Oranges	1 244 807	1 493 524
Apples	535 594	1 207 397
Bananas	366 187	840 619
Pears	339 146	745 421
Soft Citrus	137 122	406 599
Peaches	184 783	352 767
Grapefruit	363 134	285 755
Avocados	74 583	226 500
Lemons	184 214	205 205
Plums	37 080	191 956
Pineapples	166 684	156 063
Mangoes	63 881	150 902
Melons	101 810	129 825
Apricots	83 639	124 996
Other summer fruit	8 706	57 080
Papaya	14 507	47 791
Strawberries	4 620	44 917
Figs	1 519	36 140
Litchis	4 539	34 535
Guavas	28 539	33 382
Prunes	4 143	13 207
Other berries	531	8 953
Cherries	237	6 690
Granadilla	1 187	6 613
Quince	122	397
TOTAL	5 501 729	11 358 533

1.3.1 Winter rainfall region

The Western Cape province of South Africa experiences winter rainfall and has a Mediterranean-type climate. It has wet winters and hot, dry summers. In general this region also experiences fairly cold winter temperatures and thus lends itself to the production of deciduous fruit and some citrus varieties, which require cool nights for good fruit colour development and cooler winters to induce a degree of dormancy (e.g. soft citrus and Navels) (Outspan, 1997). The major climatic factors influencing where deciduous fruit can be grown successfully are humidity and summer rainfall (Rieger, 2006). Rain and humidity during the growing season promote disease and insect infestations which can decimate yield. Deciduous fruit are therefore grown in Mediterranean or arid climates.

Fruit farming forms the backbone of agriculture in the Western Cape. Fruits produced in this region include grapes (both wine and table grapes), stone fruit (peaches, plums, nectarines, apricots and prunes), pome fruit (apples and pears) and citrus (Valencias, Navels, soft citrus, lemons and pomelos). The majority of the deciduous fruit produced in South Africa is grown in the winter rainfall region of the Western Cape. The majority of prunes (93.9% of the total area of cultivated prunes in South Africa), plums (65.3%), pears (78.8%), apples (73.6%), dessert peaches (48.8%) and nectarines (65.6%) are cultivated in this region (DFPT, 2007). In addition, significant plantings of cling peaches (46.1%), apricots (15.9%) and table grapes (45.6%) are also grown in this winter rainfall region. The respective distribution of pome fruit (Figure 2), stone fruit (Figure 3) and table grapes (Figure 4) in South Africa are illustrated (DFPT, 2007).

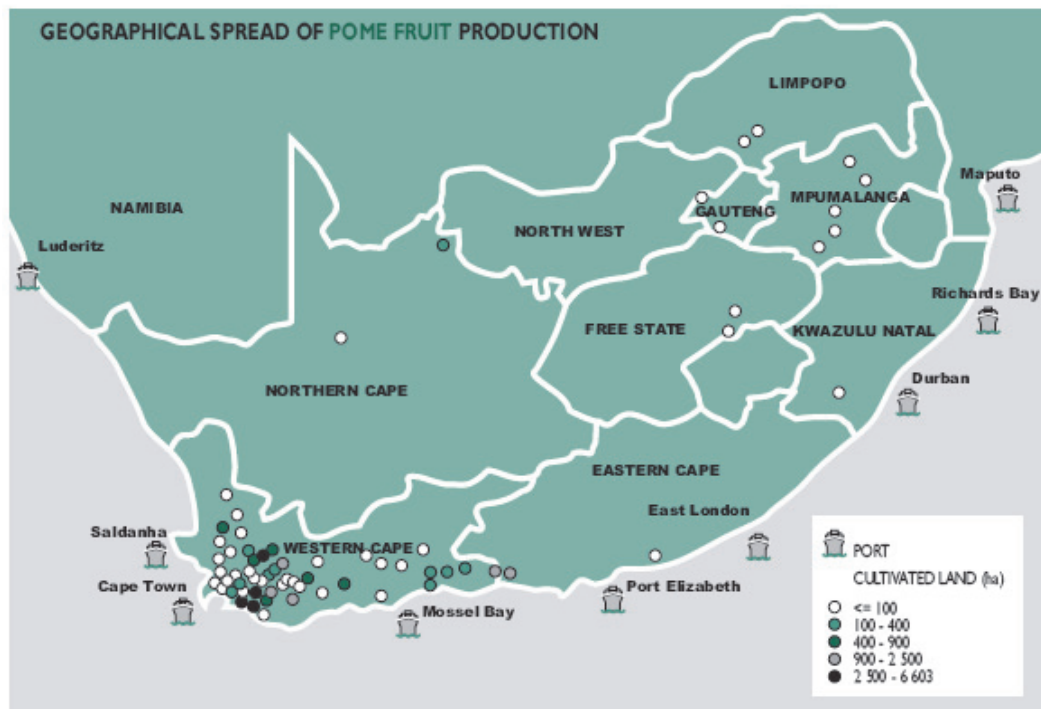


Figure 2: Pome production areas in South Africa (DFPT 2007).

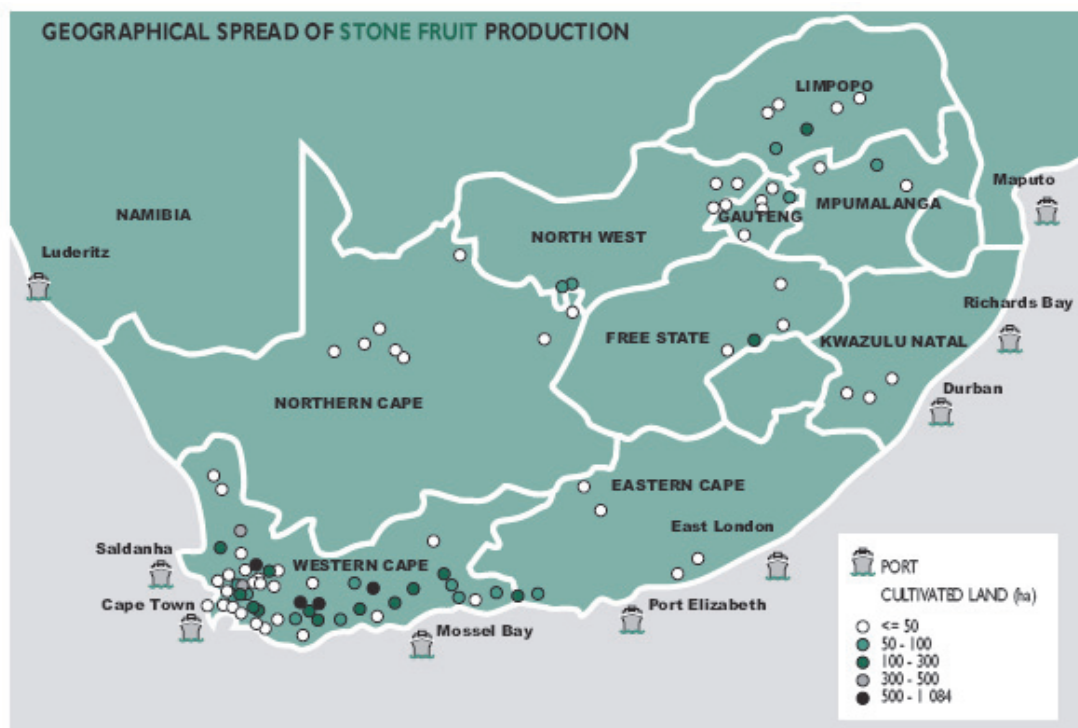


Figure 3: Stone fruit production areas in South Africa (DFPT 2007).

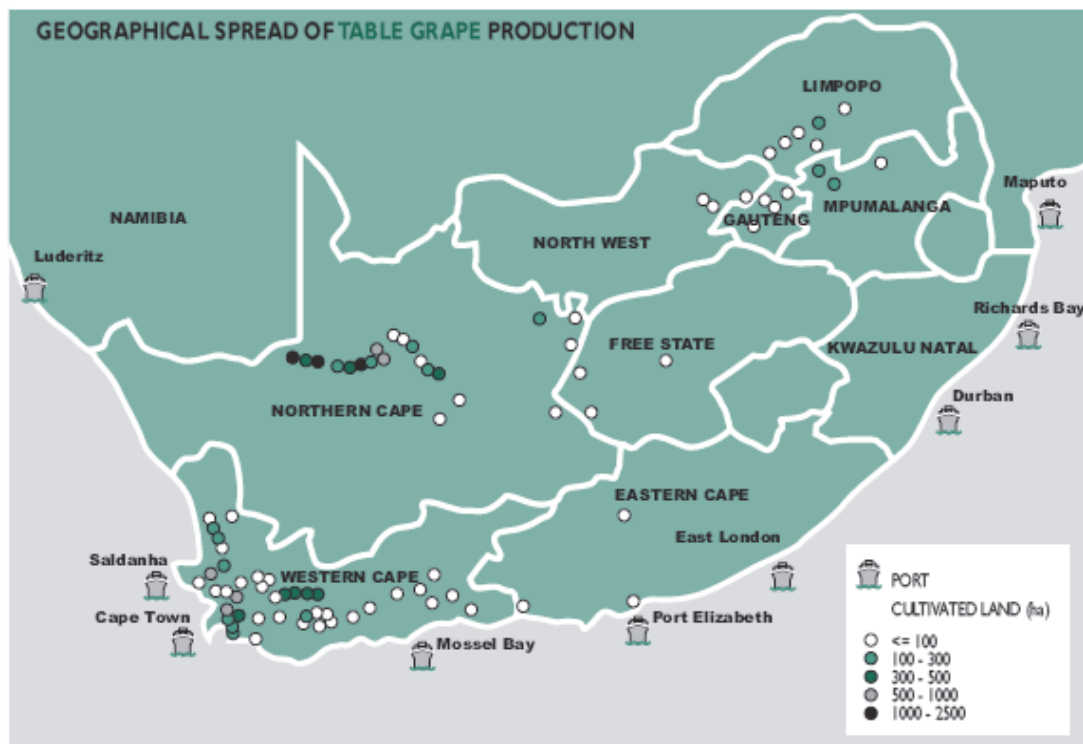


Figure 4: Table grape producing regions in South Africa (DFPT 2007).

In terms of citrus production area (ha) in South Africa, 18.6% falls within the winter rainfall region, comprising a total area of 10 033 ha (CGA 2006). This region is the most important soft citrus producing region in South African, with 51.3% of soft citrus produced here. In addition, 27.2% of Navels, 19% of lemons, 9.9% of Valencias and 9% of pomelos are produced in this winter rainfall region. Oranges with excellent peel colour are found in this region as good colour development is associated with cool nights (Outspan, 1997).

1.3.2 Summer rainfall region

Tropical fruit are only grown in the summer rainfall area and most subtropical fruit, excluding the citrus grown in the winter rainfall region of the Western Cape, are also found in this region. Deciduous fruit plantings are found in the drier summer rainfall areas, where excessive humidity in summer is not experienced.

Tropical fruit production in South Africa is limited to summer rainfall areas which are humid, low lying tropical regions, free of frost (Figure 5). The KwaZulu-Natal South Coast, Komatipoort, Kiepersol, Levubu and Tzaneen are the main production areas for bananas and papaya. Pineapples are grown in two hot and humid coastal belts of the Eastern Cape and northern KwaZulu-Natal (Dalldorf 1990a). The Eastern Cape pineapple producing area

includes Kei Mouth, East London, Kidd's Beach, Peddie, Port Alfred, Bathurst, Grahamstown, Salem and Alexandria. Pineapple production in KwaZulu-Natal is centred in the Hluhluwe area.

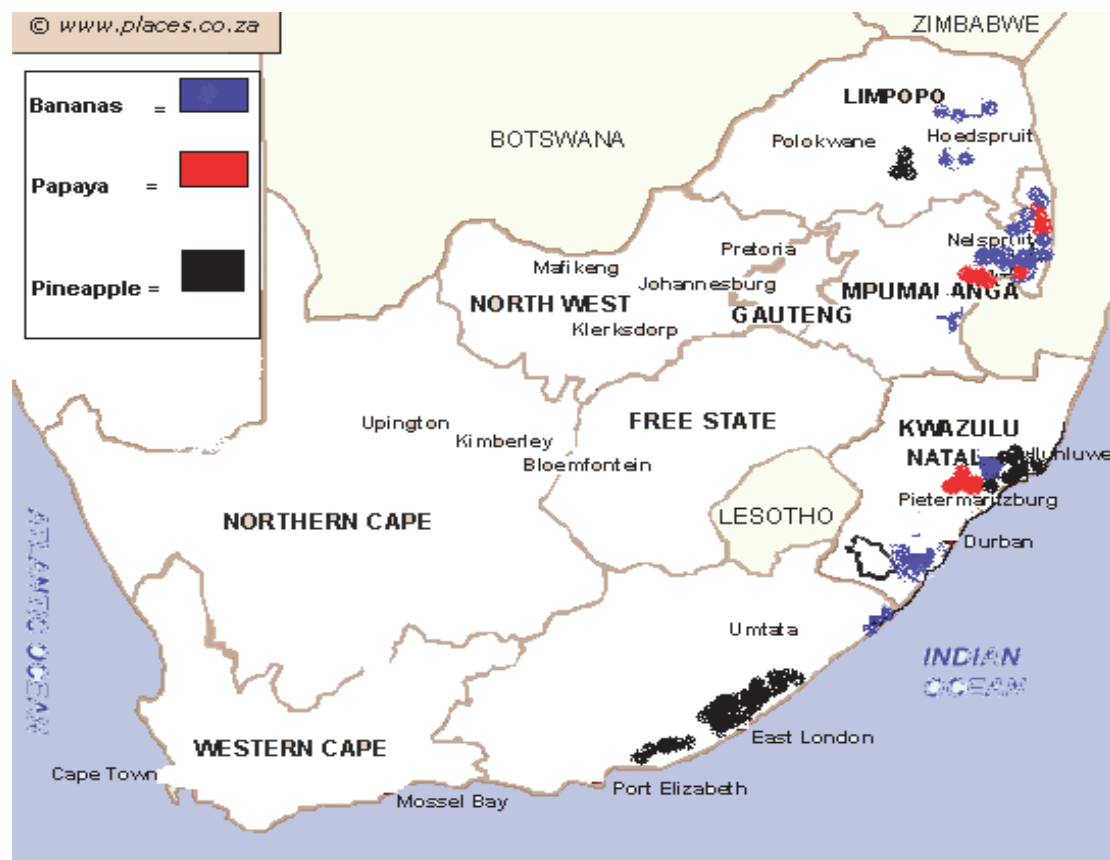


Figure 5. Distribution of tropical fruit growing areas in South Africa (Source: www.places.co.za/maps/south_africa_map.gif).

Large volumes of citrus are produced in the summer rainfall region. All the grapefruit produced in South Africa are produced in summer rainfall areas, as they have higher heat unit requirements than other citrus varieties and the production of the red pigments of some grapefruit require warm nights (Outspan, 1997). 81.1% of the total area planted to citrus is found in the summer rainfall region. The largest plantings are in the Eastern Cape (26.4%), followed by Limpopo (25.2%), Mpumalanga (21.0%), KwaZulu-Natal (7.6%) and the Northern Cape (1.2%). Valencias cover the greatest area, followed by Navels, grapefruit, lemons, Midseason oranges and pomelos.

Subtropical crops are restricted to the frost free areas of South Africa (Figure 6). Avocado production is concentrated in the warm subtropical areas of the Limpopo and Mpumalanga provinces in the north-east of the country, between 22 and 25° S of the equator. This region falls within the summer rainfall region of the country and annual rainfall in most of these areas is high (>1000 mm p.a.), but some areas are semi-arid with rainfall of around 400 mm p.a. The

most important area for avocado production is Tzaneen (38%), followed by Nelspruit (33%) and Levubu (21%). Approximately 8% of avocado orchards are found in the KwaZulu-Natal Midlands, where conditions are cooler as a result of the more southerly latitude (30° S). Heat associated with hot, dry winds has detrimental effects on pollination and fruit set (Wolstenholme, 2002) and thus avocados require humid summers.

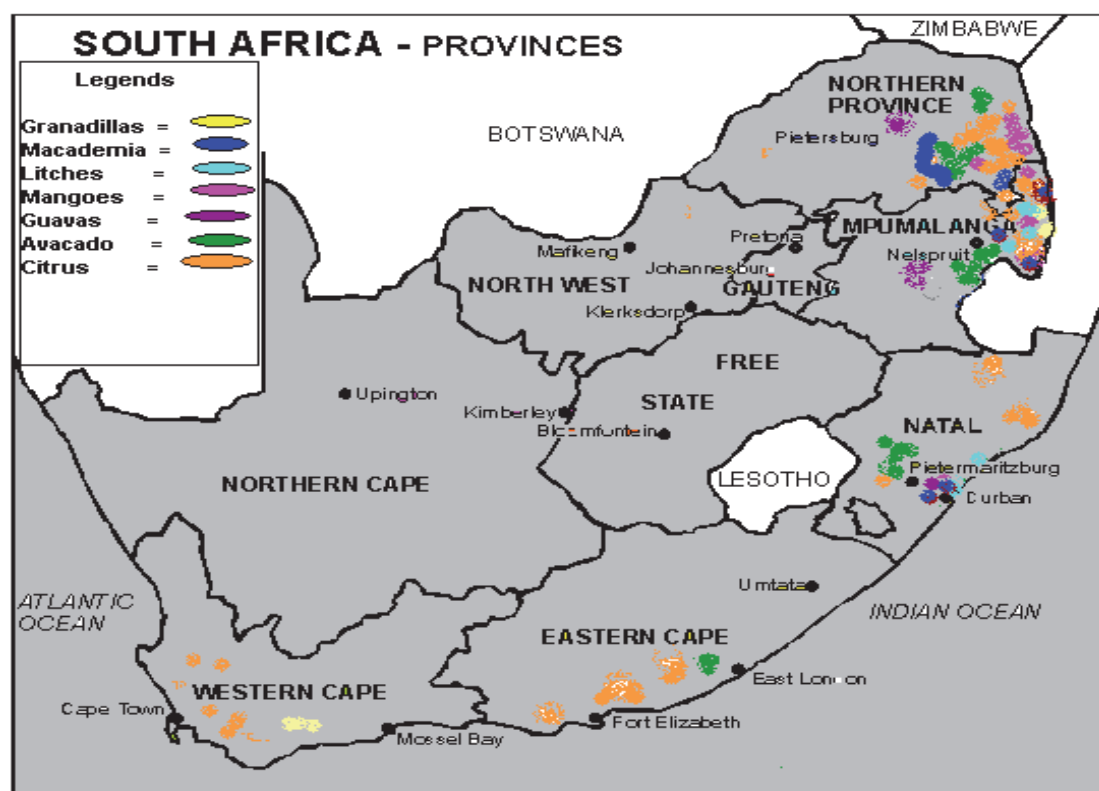


Figure 6. Distribution of subtropical fruit growing areas in South Africa (Source: <http://home.global.co.za/~mercon/samap.gif>).

The major centres for mango production are Tzaneen (38%), Hoedspruit (28%) and Malelane and Komatipoort (20%). The average annual rainfall in these growing areas varies between 300 and 1000 mm and temperatures range from 3°C (winter night) to 40°C (summer day). The main litchis producing regions are Levubu, Tzaneen/Letaba, Hazyview, Hectorspruit, Louws Creek, Malelane and Port Edward. The greatest percentage of plantings on an area basis are found in Mpumalanga (69%), followed by Limpopo (24%), KwaZulu-Natal (5%) and the Eastern Cape (1%). The main growing areas for macadamias are Levubu and Tzaneen in Limpopo province (47%), Hazyview to Barberton in Mpumalanga (35%) and coastal KwaZulu-Natal (14%). Minor plantings are found in the Eastern Cape (3%).

Pecan nuts are adapted to virtually any area with short, cold winters and long, very hot summers. The three most important factors for production are climate, soil and additional irrigation water (de Villiers 2003). The southern

Lowveld is currently the biggest production area in South Africa, with the biggest commercial planting in Nelspruit at H.L. Halls and Sons. Other important production areas include White River, Tzaneen, Louis Trichardt/Levubu, KwaZulu-Natal, the Vaalharts irrigation scheme, the Middleveld around Pretoria and some parts along the Orange River (de Villiers 2003). Ecological conditions along the Orange River in Prieska and Upington are ideal for pecan cultivation.

Deciduous fruit is produced in the dry, late summer rainfall areas, where summer humidity will not be restrictive to fruit production. The majority of table grape production, on an areas basis, occurs in the lower Orange River area (54.4% of total area). A considerable proportion of the dessert peaches are also produced in summer rainfall regions (40.4%) in the Free State and Northern Province. In addition, there are small plantings of nectarines (19.6%), plums (4.1%), apples (2.4%), prunes (2.1%), apricots (1.9%), cling peaches (1.4%) and pears (<1%). Ficksburg, in the Free State, is the most important cherry producing area in South Africa.

1.3.3 Year-round rainfall region

The all-year-round rainfall area is found in the Southern Cape region of South Africa, which is often referred to as the Garden Route. This area produces mainly deciduous fruit, with the majority of plantings occurring in the Little Karoo, where rainfall and humidity are low. The apricots grown near the town of Prince Alfred are referred to by UK retailers as the best tasting apricots in the world. Citrus is produced in Patensie in the Eastern Cape of South Africa which falls on the fringes of the all year round rainfall region. For the purposes of this review this area will fall under the Eastern Cape summer rainfall region.

This region is by far the largest apricot producing region in the country, with 82.2% of the total planted area found in this region. Most of this is centred around the Little Karoo town of Prince Albert. It also has the largest cling peach plantings with 52.5% of the total crop planted in this region, 44% of which is in the Little Karoo. There are also substantial plum (30.6%), apple (24%) and pear (21.1%) plantings and minor plantings of nectarines (14%) dessert peaches (10.8%) and prunes (4%). A small area of grapes is also planted in this region which accounts for less than 1% of the total plantings in South Africa.

1.4 Orchard layout

The fundamental principle of any cropping systems is to harvest solar radiation and convert it into an economic yield. In line with this, the grower must maximise bearing surface per hectare in the minimum amount of time (Westwood 1988). The design of any cropping system should therefore optimise radiation interception over the life of the crop, to maximize yield and yield stability. Due to access requirements, orchard crops usually only intercept about 70% of incoming solar radiation at full canopy, which may take several years to attain (Jackson 1980). Other factors such as pollinator placement (if cross pollination is required), row orientation, slope of the land, tree density (number of trees per hectare), desired tree height and training system should all be considered (Rieger, 2006). Rectangular planting patterns, where distances between rows are wider than between trees in a row are preferred as more trees can be planted per row which results in more early bearing surface. Square plantings typically waste space and make efficient removal of filler trees difficult. In addition, when the trees start touching, effective radiation penetration is prevented. High density plantings are aimed at maximising leaf surface area on available soil surface area in the shortest possible time. These systems, however, require careful management throughout the life of the orchard to limit the effect of competition between trees.

The kind of rootstock used and the arrangement of the trees will influence the ability to achieve maximum bearing surface as well as the yield sustainability of the orchard (Westwood 1988). The vigour of the trees and final tree size will have a direct bearing on tree spacing and row width, as will the need for effective pest control and other necessary orchard practices, such as pruning and harvesting. The time to bearing will also influence initial espacement, as trees that do not bear for several years are planted at wider spacings than precocious ones (Westwood 1988). Precocious trees are usually planted at high densities initially and trees are removed or thinned as the trees grow and begin to shade one another or tree manipulation is practiced to minimise shading. Shading is undesirable as it results in lower yields and poorer fruit quality. Through the use of dwarfing rootstocks permanent high density plantings can be achieved. It should be noted that there are more dwarfing rootstocks available for deciduous fruit than for subtropical fruit. Trellises are typically used to support trees on dwarfing rootstocks as they are poorly anchored (Westwood 1988). This is often undesirable for the grower as it means increased inputs.

Large trees have more shading of leaves and effective leaf area per hectare is lower than for small trees (Heinecke 1964). Radiation distribution within the

canopy impacts yield efficiency, fruit colour, fruit quality and fruit size (Westwood 1988). Most leaves are not completely shaded but are a mosaic of shaded and illuminated areas. For each leaf this changes with air movement and the angle of the sun. The photosynthetic efficiency of a given tree is, in part, a function of the proportion of the total leaf area exposed to direct sunlight multiplied by the duration of that exposure during the day (Westwood 1988).

Rows should be orientated to allow trees to intercept a maximum amount of radiation and will be determined by the latitude at which the fruit trees are planted and the crop planted. At high latitudes east-west plantings were found to intercept 9% more radiation in late summer than north-south plantings, which could aid in fruit maturation (Ferguson 1960). However, north-south plantings were found to be better for fruit set, as the north facing side of east-west rows had very poor fruit set in the Northern Hemisphere (Lombard and Westwood 1975).

1.4.1 Deciduous species

Most deciduous trees are trained to maintain tree shape and height and allow better radiation penetration into the canopy. This implies that deciduous fruit trees are generally smaller than subtropical fruit and can thus be planted at higher densities. Typically deciduous trees receive a heavy winter pruning and a lighter summer pruning to encourage the proliferation or dominance of the type of wood that bears fruit. The amount of pruning depends on the vigour of the tree and the type of wood on which the fruit are borne. Grapes are pruned more severely than any other crop.

A wide range of orchard designs and training systems are permissible for apple trees due to the availability of a wide range of rootstocks. In most cases, however, trees are grown in rectangular blocks or hedgerows. In South Africa apple and pear trees are generally planted in hedgerows at 1.5 m x 4 m. Pears and apples require cross-pollinators, which are included in alternate rows or every 10th or 15th tree within hedgerows (Rieger 2006).

Apricots require good light penetration for fruit colour development and as they do not require cross-pollinators they can be planted in solid blocks. Spacing of 6-7 m between rows and trees can be employed if vigorous rootstocks are used but if less vigorous rootstocks are used the trees can be planted closer together.

Free standing peach orchards use rectangular planting systems of 5.5 x 6 m or 3.5-4.5 x 5.5 m, but trellised systems can be planted at higher densities. Different cultivars for cross-pollination are not required but different cultivars should be planted in the same orchard to extend the marketing season.

Japanese plum trees are smaller than European plum trees and can therefore be planted at a closer spacing. Japanese plums are planted with 3-6 m in row distances and 5.5 m to 6 m between row distances, depending on the size of the equipment that has to move between rows. Cross pollination is required and thus pollinator species should be planted in alternate rows or about every 3rd tree in every 3rd row (Rieger 2006). Plums that are grown for prunes do not require cross pollination.

Vine and shrub species are generally planted at higher densities than orchard species, although planting densities vary greatly (Westwood 1988). The highest densities are with the small species, such as strawberry. Grapes are trellised and grown in long narrow rows, which are spaced about 3-4.5 m apart, with the vines spaced 1-2.5 m within the row (Rieger 2006).

1.4.2 Tropical and subtropical species

Single-stemmed species do much better in equidistant patterns, whilst branched trees are more suited to row cropping in rectangular patterns (Verheij 1985). High density orchards are used for subtropical fruit for two reasons, firstly, to achieve commercial production sooner and secondly, to force growers to keep the trees smaller, more efficient and manageable (Stassen and Davie 1996a). Guidelines for semi-intensive and intensive planting distances for some subtropical fruit trees are given (Table 2).

Table 2. Guidelines for planting distances (m) for different crops (rootstocks, soils and climate must be taken into account and management strategies adapted accordingly) (Stassen and Davies 1996).

Crop/Cultivar	(a) Standard semi-intensive planting (a degree of manipulation is still necessary) (m)	(b) Intensive (for specific training system, manipulation techniques, rootstocks and soil types) (m)
Avocados		
Ryan	5 x 3	4 x 1.5
Hass	6 x 3	5 x 2.5
Fuerte	7 x 3.5	6 x 3
Edranol	5 x 3	5 x 2
Pinkerton	5 x 3	4 x 1.5
Citrus		
Grapefruit	6 x 3	5 x 2
Oranges	5 x 2.5	4 x 1.5
Lemons	5 x 2	4 x 1.25
Mandarins	5 x 2	4 x 1.25
Mangoes		
Sensation	5 x 2.5	4 x 1.5
Tommy Atkins	6 x 3	5 x 2
Heidi	5 x 2.5	4 x 1.5
Keitt	6 x 3.5	5 x 2.5
Kent	6 x 3	5 x 2
Litchis		
	5 x 3	4 x 1.5
Guavas		
	5 x 3	4 x 1.5
Macadamia		
Beaumont	5 x 2	4 x 1.5
Kau	5 x 3	5 x 2
Fuji	5 x 3	5 x 2
Nelmak II	7 x 3.5	5 x 2
Pahala	5 x 3	5 x 2
816	5 x 3	5 x 2

When planted at high densities some form of dwarfing or tree manipulation is required to control the size of the tree in order to reduce or delay competition for light, nutrients and water between trees. The ideal tree shape is conical or pyramidal and the narrower the tree, the more the side shoots are spirally developed around a central leader and the greater the light penetration (Stassen and Davie 1996a). The tree height should not exceed 80% of the width between rows or twice the free working space between rows. This helps to minimise overshadowing by the top of one row on the bottom of another and allows for harvesting by hand. Spatial orientation of the trees should be such that optimal light is intercepted by the canopy during the day depending on the sun's movement across the horizon (Stassen and Davie 1996a). In the Southern Hemisphere this will normally be a north-south orientation but will depend on latitude, citing, occurrence of sunburn and other practical considerations such as slope. A north-south orientation allows light interception by the eastern side for 50% of the time and on the western side for the other 50% of the time (Stassen and Davie 1996a). Hedgerow plantings are efficient in intercepting radiation and minimising the amount of light reaching the ground, and they allow for the greatest amount of the canopy to receive optimum light density (Outspan 1997). As a result, hedgerows have greater bearing volume. The work-row between hedgerows is required for implement movement within the orchard but the primary purpose is to allow sufficient light interception by the whole leaf canopy of the hedgerow. The selection of orchard layout and planting density should strike a balance between simplicity and complexity to match the skills available to manage and maintain the orchard (Whiley 2002).

Avocados

If land is inexpensive then it is possible to have large spaces between rows (10 x 8 m to 12 x 9 m, giving 92-120 trees ha⁻¹). The disadvantages of such wide spacing is that lower returns can be expected in the early life of the orchard and eventually larger trees result which have poor fruit quality and increased harvesting costs (Hofshi 1999). The advantages include lower tree removal costs and generally fewer management inputs e.g. irrigation and fertilizer (Newett *et al.*, 2001). Stassen and co-workers (1995a, b) have proposed that to meet the requirements of modern day avocado production at least 500 trees ha⁻¹ should be planted and maintained as productive units throughout the life of the orchard. To maintain a productive hedgerow it is recommended that the trees be pruned immediately following harvest with further maintenance pruning during summer to ensure that light interception and penetration is not compromised, thus keeping the lower canopy productive (Stassen *et al.*, 1995a, b). This intensive pruning regime can, however, lead to a decline in productivity. Most of the pruning is done by machines.

Modern day avocado orchards are shifting towards medium to high density plantings (6 x 4 to 9 x 7 m, giving 159-416 trees ha⁻¹). Under South African conditions Köhne and Kremer-Köhne (1990, 1991) demonstrated that through high density plantings (800 trees ha⁻¹) a positive return on investment can be achieved earlier than standard planting densities (400 trees ha⁻¹). Trees at densities of 800 trees ha⁻¹ reach maximum leaf surface area within 4 years, whilst at 400 trees ha⁻¹ trees reach the same stage after 8 years.

Planting to a hedgerow layout, without the necessity to remove trees, is becoming commonly accepted. A north-south orientation is favoured to maximise light interception, which becomes important at higher latitudes. A hedgerow which is mechanically pruned to a pyramidal shape is becoming popular in South Africa in situations where the topography allows the passage of large equipment through orchards. Hedgerows that are mechanically pruned are pruned twice a year, immediately following harvest (autumn/winter) and in summer. Continual mechanical hedging results in a solid wall of vegetation which limits light penetration, strategic removal of large limbs in the side walls allows better light penetration and should take place on an annual basis.

Citrus

High density plantings for citrus are defined as having more than 1000 trees ha⁻¹, whilst conventional plantings have less than 1000 trees ha⁻¹ (Outspan 1997). The rectangular planting system, with single, double or intermediate planting distances, is the most popular conventional planting system. Under single planting distances trees within rows should not touch each other, even when fully grown and there is room between rows for machinery. Under double planting distances trees are planted in rows at twice the density of single planting and can produce yields in the first 6 years which are double those of single plantings (Outspan 1997). Intermediate spacing distances ensure that maximum yield can be obtained by an orchard without serious problems of overcrowding. Canopies are calculated to touch each other after achieving 75-80% of their final size.

Hedgerow plantings in citrus should be orientated north-south. This is of particular importance in the Western Cape, which has a winter rainfall climate, in order to ensure adequate drying of the orchard for harvesting (Outspan 1997). It also gives a more even distribution of light between the two sides of the canopy than an east-west orientation. This is important in the southern latitudes as the soil on the south side of an east-west orientation remains moist for too long, thus promoting root disease. Shading also increases the incidence of various insects including the vector for "greening disease". In

situations where north-south orientations are not possible, wider tree spacing should be considered to allow better light penetration and air movement. The recommended roadway allocation between rows is 2.5 m, which should be at least 50% of the final tree height (Outspan 1997). Tree growth rates are the main determining factor of in-row and between-row planting distances. Tree growth is influenced by a number of factors including climate, soil type, rootstock and scion vigour, cultural practices and disease. Citrus trees at intermediate planting distances, apart from grapefruit, should be allowed to form a hedgerow between 16 and 18 years, whilst grapefruit trees should be allowed to form hedgerows between 9 and 10 years (Outspan 1997). High density plantings should, however, be allowed to form hedgerows sooner.

High density plantings are used in citrus, as time to potential optimal yield is reduced at higher densities. For example, Valencia oranges planted at a spacing of 7 x 7 m will only achieve the targeted 80 t ha⁻¹ after at least 20 years, however if spacing is reduced to 7 x 4 m it will require 10-12 years and if planted even closer at 5 x 2.5 m it can be achieved within 6 years or less (Stassen and Davie 1996a).

Recommended tree spacing for hot and very hot areas (Letsitele, Lower Letaba, Hoedspruit, Limpopo Valley, Malalane, Pongola and Nkwalini) are given (Table 3); for intermediate areas (Marble Hall, Nelspruit, Hazyview, Barberton, White River, Letaba and Levubu) (Table 4); for cool areas (Rustenburg, Potgietersrus, Lydenburg/Burgersfort and Zebediela) (Table 5); and for cold areas (Eastern Cape Midlands, Gamtoos River Valley, Sundays River Valley, Amanzi, Southern Kwazulu-Natal, South-Western Cape, Citrusdal, Knysna and surrounding areas and Vaalharts) (Table 6).

Table 3. Recommended tree spacing for the hot/very hot areas of South Africa (Outspan, 1997).

CULTIVARS	ROOTSTOCKS*									
	RL	VA	CM	SC	TC/CC	YC	EM	X639	MxT	TR
Grapefruit										
Star Ruby	X [*]	X	6.0-7.0X2.5-3.5	6.0-7.0X2.5-3.5	6.0-6.5x2.0-3.0	6.0-6.5x2.0-3.0	6.0-6.5x2.0-3.0	6.0-6.5x2.0-3.0	6.0-6.5x2.0-3.0	5.5-6.0x2.0-2.5
Other	6.5-7.5x3.0-3.5	X	6.5-7.5X3.0-4.0	6.5-7.5X3.0-4.0	6.5-7.0x2.5-3.5	6.5-7.0x2.5-3.5	6.5-7.0x2.5-3.5	6.5-7.0x2.5-3.5	6.5-7.0x2.5-3.5	6.0-6.5x2.5-3.0
Valencias										
Delta	X	X	6.5-7.5x3.5-4.0	6.5-7.5x3.5-4.0	6.5-7.0X3.0-3.5	6.5-7.0X3.0-3.5	6.5-7.0X3.0-3.5	6.5-7.0X3.0-3.5	6.5-7.0X3.0-3.5	6.0-6.5x2.5-3.0
Other	6.5-7.5x3.5-4.0	X	6.5-7.5x3.5-4.0	6.5-7.5x3.5-4.0	6.5-7.0X3.0-3.5	6.5-7.0X3.0-3.5	6.5-7.0X3.0-3.5	6.5-7.0X3.0-3.5	6.5-7.0X3.0-3.5	6.0-6.5x2.5-3.0
Lemons										
Eureka	7-8x3-4	7-8x3-4	7-8x3-4	X	X	X	7.0-7.5x3.0-3.5	7.0-7.5x3.0-3.5	7.0-7.5x3.0-3.5	X
Midseason										
Tomango	6.5-7.5x3.5-4.0	X	6.5-7.5x3.5-4.0	X	X	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	X
Clanor	X	X	6.5-7.5x3.5-4.0	X	X	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	X	X	X
Mandarin										
Minneola	7.0-7.5x3.5-4.0	X	7.0-7.5x3.5-4.0	7.0-7.5x3.5-4.0	6.5-7.0X3.0-3.5	X	X	6.5-7.0X3.0-3.5	X	6.0-6.5x2.5-3.0
Pomelo										
Pomelit	X	X	6.0-7.0X2.5-3.5	6.0-7.0X2.5-3.5	6.0-6.5X2.0-3.0	X	6.0-6.5X2.0-3.0	X	X	X
Oroblanco	X	X	X	6.0-7.0X2.5-3.5	6.0-6.5X2.0-3.0	X	X	X	X	X

* (RL-Rough Lemon, VA-Volckameriana, CM-Cleopatra mandarin, SC-Swingle citrumelo, TC-Troyer citrange, CC-Carrizo citrange, YC-Yuma citrange, EM-Empress mandarin, X639-Cleopatra X Trifoliata, MxT-Minneola X Trifoliata, TR-Trifoliata). X – combination is not recommended or insufficient information available.

Table 4. Recommended tree spacing for the intermediate areas of South Africa (Outspan, 1997).

CULTIVARS	ROOTSTOCKS									
	RL	VA	CM	SC	TC/CC	YC	EM	X639	MxT	TR
Grapefruit										
Star Ruby	X [*]	X	6.0-7.0x2.5-3.5	6.0-7.0x2.5-3.5	6.0-6.5x2.0-3.0	6.0-6.5x2.0-3.0	6.0-6.5x2.0-3.0	6.0-6.5x2.0-3.0	6.0-6.5x2.0-3.0	5.5-6.0x2.0-2.5
Marsh	6.5-7.5x3.0-3.5	X	6.5-7.5x3.0-4.0	6.5-7.5x3.0-4.0	6.5-7.0x2.5-3.5	6.5-7.0x2.5-3.5	6.5-7.0x2.5-3.5	6.5-7.0x2.5-3.5	6.5-7.0x2.5-3.5	6.0-6.5x2.5-3.0
Valencias										
Midknight	6.0-7.0x3.0-3.5	X	6.5-7.5x3.5-4.0	6.5-7.5x3.5-4.0	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	X
Other	6.5-7.5x3.5-4.0	X	6.5-7.5x3.5-4.0	6.5-7.5x3.5-4.0	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.0-6.5x2.5-3.0
Navels										
Bahianinha	6.0-7.0x3.0-3.5	X	6.0-7.0x3.0-3.5	6.0-7.0x3.0-3.5	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	5.5-6.0x2.0-2.5
Other	6.5-7.5x3.5-4.0	X	6.5-7.5x3.5-4.0	6.5-7.5x3.5-4.0	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.0-6.5x2.5-3.0
Lemons										
Eureka	7-8x3-4	7-8x3-4	7-8x3-4	X	X	X	7-7.5x3-3.5	7-7.5x3-3.5	7-7.5x3-3.5	X
Midseason										
Tomango	6.5-7.5x3.5-4.0	X	6.5-7.5x3.5-4.0	X	6.5-7.0x3.0-3.5	X	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	X
Clanor	X	X	6.5-7.5x3.5-4.0	X	6.5-7.0x3.0-3.5	X	6.5-7.0x3.0-3.5	X	X	X
Shamouti	6.5-7.5x3.5-4.0		6.5-7.5x3.5-4.0	X	6.5-7.0x3.0-3.5	X	6.5-7.0x3.0-3.5	X	X	X
Mandarins										
Minneola	7.0-7.5x3.5-4.0	X	7.0-7.5x3.5-4.0	7.0-7.5x3.5-4.0	6.5-7.0x3.0-3.5	X	X	6.5-7.0x3.0-3.5	X	6.0-6.5x2.5-3.0
Nova	X	X	6.0-7.0x3.0-3.5	6.0-7.0x3.0-3.5	6.0-6.5x2.5-3.0	X	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	X	X

[#](RL-Rough Lemon, VA-Volkameriana, CM-Cleopatra mandarin, SC-Swingle citrumelo, TC-Troyer citrange, CC-Carrizo citrange, YC-Yuma citrange, EM-Empress mandarin, X639-Cleopatra X Trifoliata, MxT-Minneola X Trifoliata, TR-Trifoliata). X – combination is not recommended or insufficient information available.

Table 5. Recommended tree spacing for the cool areas of South Africa (Outspan, 1997).

CULTIVARS	ROOTSTOCKS									
	RL	VA	CM	SC	TC/CC	YC	EM	X639	MxT	TR
Valencias										
Midknight	6.0-6.5x2.5-3.0	X	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	5.5-6.5x2.5-3.0	5.5-6.5x2.5-3.0	5.5-6.5x2.5-3.0	5.5-6.5x2.5-3.0	5.5-6.5x2.5-3.0	5.5-6.0x2.0-2.5
Other	6.5-7.0x3.0-3.5	X	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	5.5-6.0x2.5-3.0
Navels										
Bahianinha	5.5-6.5x2.5-3.0	X	5.5-6.5x2.5-3.0	5.5-6.5x2.5-3.0	5.5-6.0x2.0-2.5	5.5-6.0x2.0-2.5	5.5-6.0x2.0-2.5	5.5-6.0x2.0-2.5	5.5-6.0x2.0-2.5	5.0-5.5x2.0-2.5
Other	6.0-7.0x3.0-3.5	X	6.0-7.0x3.0-3.5	6.0-7.0x3.0-3.5	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	5.5-6.0x2.5-3.0
Lemons										
Eureka	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	X	X	X	6.0-6.5x3.0-3.5	6.0-6.5x3.0-3.5	6.0-6.5x3.0-3.5	X
Midseason										
Tomango	6.0-7.0x3.0-3.5	X	6.0-7.0x3.0-3.5	X	6.0-6.5x2.5-3.0	X	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	6.0-6.5x2.5-3.0	X
Clanor	X	X	6.0-7.0x3.0-3.5	X	6.0-6.5x2.5-3.0	X	6.0-6.5x2.5-3.0	X	X	X
Shamouti	6.0-7.0x3.0-3.5	X	6.0-7.0x3.0-3.5	X	6.0-6.5x2.5-3.0	X	6.0-6.5x2.5-3.0	X	X	X
Mandarins										
Minneola	6.5-7.0x3.0-3.5	X	6.5-7.0x3.0-3.5	6.5-7.0x3.0-3.5	6.0-6.5x2.5-3.0	X	X	6.0-6.5x2.5-3.0	X	X
Nules	X	X	5.5-6.0x2.5-3.0	5.5-6.0x2.5-3.0	5.5-6.0x2.0-2.5	5.5-6.0x2.0-2.5	5.5-6.0x2.0-2.5	5.5-6.0x2.0-2.5	X	X
Nova	X	X	5.5-6.0x2.5-3.0	5.5-6.0x2.5-3.0	5.5-6.0x2.0-2.5	X	5.5-6.0x2.0-2.5	5.5-6.0x2.0-2.5	X	X

*(RL-Rough Lemon, VA-Volkameriana, CM-Cleopatra mandarin, SC-Swingle citrumelo, TC-Troyer citrange, CC-Carizo citrange, YC-Yuma citrange, EM-Empress mandarin, X639-Cleopatra X Trifoliata, MxT-Minneola X Trifoliata, TR-Trifoliata). X – combination is not recommended or insufficient information available.

Table 6. Recommended tree spacing for the cold areas of South Africa (Outspan, 1997).

CULTIVARS	ROOTSTOCKS									
	RL	VA	CM	SC	TC/CC	YC	EM	X639	MxT	TR
Valencias Midknight	5.0-6.0x2.0- 2.5	X	5.0-56.0x2.0- 2.5	5.0-6.05x2.0- 2.5	5.0-5.5x2.0- 2.5	5.0-5.5x2.0- 2.5	5.0-5.5x2.0- 2.5	5.0-5.5x2.0- 2.5	5.0-5.5x2.0- 2.5	X
Navels Bahianinha Other	5.5-6.0x2.0- 2.5 6.0-6.5x2.5- 3.0	X X	5.5-6.0x2.0- 2.5 6.0-6.5x2.5- 3.0	5.5-6.0x2.0- 2.5 6.0-6.5x2.5- 3.0	5.0-5.5x2.0- 2.5 5.5-6.0x2.5- 3.0	5.0-5.5x2.0- 2.5 5.5-6.0x2.5- 3.0	5.0-5.5x2.0- 2.5 5.5-6.0x2.5- 3.0	5.0-5.5x2.0- 2.5 5.5-6.0x2.5- 3.0	5.0-5.5x2.0- 2.5 5.5-6.0x2.5- 3.0	5.0-5.5x2.0- 2.5 5.5-6.0x2.5- 3.0
Lemons Eureka	6.0-6.5x2.5- 3.0	6.0-6.5x2.5- 3.0	6.0-6.5x2.5- 3.0	X	X	X	5.5-6.0x2.5- 3.0	5.5-6.0x2.5- 3.0	5.5-6.0x2.5- 3.0	X
Midseason Shamouti	6.0-6.5x2.5- 3.0	X	6.0-6.5x2.5- 3.0	X	5.5-6.0x2.5- 3.0	X	5.5-6.0x2.5- 3.0	X	X	X
Mandarins Minneola Miho-Wase Owari Nules Oroval Nova	6.0-6.5x2.5- 3.0 X X 5/5-6.0x2.0- 2.5 X X	X X X X X X X	X X 5.0-5.5-2.0-2.5 5/5-6.0x2.0- 2.5 5/5-6.0x2.0- 2.5 5/5-6.0x2.0- 2.5	X X 5/0-5.5x2.0- 2.5 5/5-6.0x2.0- 2.5 5/5-6.0x2.0- 2.5	X 4.5-5.0x2.0- 2.5 4.5-5.0x2.0- 2.5 5/0-5.5x2.0- 2.5 5/0-5.5x2.0- 2.5 5/0-5.5x2.0- 2.5	X X X X X X X	X X 4.5-5.0x2.0- 2.5 4.5-5.0x2.0- 2.5 5/0-5.5x2.0- 2.5 5/0-5.5x2.0- 2.5 5/0-5.5x2.0- 2.5	X 4.5-5.0x2.0- 2.5 4.5-5.0x2.0- 2.5 X X X X	X 4.5-5.0x2.0- 2.5 4.5-5.0x2.0- 2.5 X X X X	X 4.5-5.0x2.0- 2.5 4.5-5.0x2.0- 2.5 X X X X

#(RL-Rough Lemon, VA-Volkameriana, CM-Cleopatra mandarin, SC-Swingle citrumelo, TC-Troyer citrange, CC-Carizo citrange, YC-Yuma citrange, EM-Empress mandarin, X639-Cleopatra X Trifoliolate, MxT-Minneola X Trifoliolate, TR-Trifoliolate). X – combination is not recommended or insufficient information available.

Mango

The latest trend in mango plantings is high density plantings with a hedgerow system. Inter row spacing is 5-6 m and intra row tree spacing is 2-3 m. As a result tree density is between 555 and 1000 trees ha⁻¹. New pruning techniques are being employed like tipping and topping (Oosthuysen, 1993) to increase the number of bearing shoots per tree and increase the productivity of young orchards. Young 3-4 year old trees are more productive as a result of these cultural practices than older trees planted at a tree density of 250 trees ha⁻¹.

Macadamia

Older orchards were planted with trees 10 to 12 m apart. Due to the long period required for the tree to fill this space it is now the tendency to plant at a closer spacing. The closest planting distance for macadamias has been determined to be 3 m in the row and 5 m between rows (SAMAC, 2007). More precocious varieties can be planted as inter plants in high density plantings, as they come into production earlier than the traditional cultivars and can be thinned after 8-12 years.

Pecan

The tendency in pecans, as with macadamias, is to move away from wider spacing and to plant at a closer spacing (de Villiers 2003). In order to maximise yield as many trees as possible should be planted per hectare but then the grower needs to take into account pruning, fertilization and irrigation. In these high density plantings trees are usually thinned as soon as they overshadow each other (age 12-15 years, depending on the region in which they are grown). If they are not pruned then diagonal rows will have to be removed. The orchard layout will depend on the region in which the pecan is grown i.e. are trees slow or fast growing. Trees should be kept small by pruning to fit in with the closer spacing and although yield per tree is lower for small trees than big trees, yield per hectare is greater. Three cultivars should be planted in an orchard or block to ensure adequate cross pollination.

Banana

The spacing in banana orchards varies in accordance with cultivar height at maturity. Plantations are laid out in hexagonal or bedded designs. Bedded designs have double or triple rows followed by a row for the movement of machines. It is recommended that 1666 trees ha⁻¹, as higher plant numbers result in a greater time to harvest and a greater harvest spread which do not offset the increased yields. Rectangular plantings are better than hedgerows or tramlines. The different growth strategy of banana relative to other tropical and subtropical fruit species (Verheij 1985) means that orchard layout

strategies are different. Yield does not increase linearly with increase in the plant population (Robinson 1996).

Pineapples

The main aims, when designing a pineapple orchard, are to minimise water runoff and therefore erosion; to facilitate maximum drainage to prevent the build-up of *Phytophthora* spp. in the soil; and to have roads through which machinery can access the pineapple plants (Dalldorf 1990c). Soil type, slope, degree of mechanisation, topography, climate, soil-conservation methods, aspect and natural obstacles will all influence orchard layout. Slopes exceeding 20% should not be planted with pineapples as machinery movement is difficult on such slopes and soil losses are difficult to prevent. The occurrence and intensity of rainfall is one of the most important factors when considering land layout. On cool, south slopes and in the cooler pineapple producing regions it is advisable to plant in a north-south direction rather than an east-west direction as in this orientation the south row grows poorly as a result of shading by a more vigorously growing north row (Dalldorf 1990c). Shading can have a dramatic effect on yield and must be taken into account.

Competition between plants needs to be avoided for good yield of good quality fruit. Plants need abundant sunlight and sufficient rooting area (Dalldorf 1990d). Planting density affects fruit size in a highly predictable manner (Bartholomew and Paull 1986). Average fruit size decreases linearly as plant population increases. The relationship between plant spacing, plant size and fruit size can, however, be exploited for the canning industry where smaller fruits have better shape for the canning (Dalldorf 1990).

Smooth Cayenne pineapples are generally planted in double rows 60 cm apart, such that each plant supports its neighbour, thereby preventing lodging (Dalldorf 1990d). Plant populations of 39 141 plants/ha (107 x 61 x 30.5 cm), 41 667 plants/ha (100 x 60 x 30 cm) and 43080 plants/ha (99 x 53.3 x 30.5 mm) all give good yields, but as soon as plant populations increase above 45 000 plants/ha yield and quality decreases. Single rows are popular with 'Queen' pineapples as lodging is not an issue. Planting densities depend on the starting propagation material i.e. stumps versus suckers. Suckers can be planted at higher densities (Dalldorf 1990d). 'Queen' pineapples have been planted successfully in triple rows with a spacing of 75 x 37 x 37 x 22 cm (91 519 plants/ha) and at even higher densities of 100 000 plants/ha. Queen stumps are used in some regions and give good yields when planted in double rows with densities similar to 'Smooth Cayenne'. Good yields are obtained when stumps are planted in single rows at 101.6 x 30.5 cm (22 280 plants/ha) and 121.9 x 30.5 cm (26 920 plants/ha) (Dalldorf 1990d).

Papaya

Planting distances within the row should be at least 2.0 m and between the rows approximately 3.0-3.5 m. Double rows can also be planted 2 m apart with 3.5 m on either side of the double row (Botha 1979). Spacing less than 3.0 m gives rise to tall plants which produce fruit high up on the plant, making harvesting difficult. Increased inter plant competition can also impact on yield. Papayas are dioecious and thus provision must be made to include male trees in the orchard, about one male tree for every 20 female trees.

1.5 Fruit types / cultivars grown in South Africa and their relative importance

1.5.1 Deciduous species

A vast array of cultivars is available for deciduous fruit trees. Importantly cultivars have been selected with low chill requirements, allowing the cultivation of deciduous fruit in a wide variety of climatic zones. Many of the new cultivars have been bred in South Africa and are ideally suited to the South African climate.

Table grapes are the most widely produced deciduous fruit in South Africa, accounting for 30% of the total area planted to deciduous fruit. The second most important deciduous fruit is apple (28%), followed by pears (16%), peaches (12%), apricots (6%), plums (5%), nectarines (2%) and finally prunes (1%).

There are 17 grape cultivars which each constitute more than 1% of the total table grape planted area (Table 7). The most important table grape cultivar in South Africa is 'Thompson seedless' (34% of the total planted area) and the grapes from this cultivar are commonly referred to as sultanas. A number of apple and pear cultivars are grown in South Africa. The most important apple cultivars include 'Granny Smith' (25%), 'Golden Delicious' (22%) and 'Royal Gala' (12%) (Table 8), while the most important pear cultivars are 'Packham's Triumph' (28%), 'Forelle' (22%) and 'Williams Bon Chretien' (20%) (Table 9).

Table 7. Area planted per grape cultivar in South Africa in 2006 (DFPT 2006).

Cultivar	Area planted (ha)	% of total planted area
Thompson seedless/ Sultana	7 834	34
Red Globe	1 529	7
Sugraone	1 454	6
Crimson Seedless	1 431	6
Flame Seedless	1 273	6
Dauphine	1 268	6
Prime	1 251	5
Merbein Seedless	835	4
Regal Seedless	833	4
Sunred Seedless	619	3
Barlinka	617	3
La Rochelle	617	3
Korent	409	2
Waltham Cross	409	2
Victoria	406	2
Dan Ben Hannah	398	2
Alphonse Lavallee	344	1
Other Grapes	1 432	6
TOTAL	22 959	100

Table 8. Area planted per apple cultivar in South Africa in 2006 (DFPT 2006).

Cultivar	Area planted (ha)	% of total planted area
Granny Smith	5 259	25
Golden Delicious	4 498	22
Royal Gala	2 410	12
Pink Lady	1 382	7
Starking	1 241	6
Topred	1 282	6
Fuji	825	4
Braeburn	689	3
Other	3 052	15
TOTAL	20 633	100

Table 9. Area planted per pear cultivar in South Africa in 2006 (DFPT 2006).

Cultivar	Area planted (ha)	% of total planted area
Packham's Triumph	3 301	28
Williams Bon Chretien	2 326	20
Forelle	2 539	22
Early Bon Chretien	1 016	9
Rosemarie	428	4
Beurre Bosc	412	4
Abate Fetel	384	3
Doyenne Du Comice	294	3
Other	848	7
TOTAL	11 548	100

A large number of stone fruit cultivars grown in South Africa have been bred locally and some of these cultivars are performing extremely well. Dessert peach plantings in South Africa consist of a very wide range of cultivars, with the most important cultivar being 'Transvalia' (14%) (Table 10). There are also a large number of cling peach cultivars, with the most important four being 'Kakamas' (18%), 'Keisie' (18%), 'Oom Sarel' (15%) and 'Prof Neethling' (13%) (Table 11). Cling peaches are planted over a wider area than dessert peaches i.e. 7 422 ha versus 1 317 ha (DFPT 2006). The majority of apricot plantings consist of the cultivar 'Bulida' (52%) followed by 'Soldonné' (9%) and 'Palsteyn' (9%) (Table 12). A wide variety of plum cultivars are planted in South Africa, a large number of which are of South African origin. The most important cultivar is 'Songold' (17%), followed by 'Laetitia' (16%) and 'Sapphire' (10%) (Table 13). The two most important nectarine cultivars are 'Alpine' (17%) and 'May Glo' (10%) (Table 14). Only a few prune cultivars are planted in South Africa, with two cultivars make up the majority of the plantings, namely 'Van Der Merwe' (55%) and 'Erfdeel' (26%) (Table 15).

Table 10. Area planted per dessert peach cultivar in South Africa in 2006 (DFPT Tree Census 2006).

Cultivar	Area planted (ha)	% of total planted area
Tansvalia	188	14
San Pedro	83	6
Sunsweet	69	5
Suncrest	65	5
Fairtime	63	5
Nova Donna	62	5
Elberta	54	4
Witzenberg	48	4
Others	685	52
TOTAL	1 317	100

Table 11. Area planted per cling peach cultivar in South Africa in 2006 (DFPT Tree Census 2006).

Cultivar	Area planted (ha)	% of total planted area
Kakamas	1 394	18
Keisie	1 338	18
Oom Sarel	1 082	15
Prof Neethling	974	13
Sandvliet	702	9
Western Sun	496	7
Prof Malherbe	343	5
Woltemade	260	4
Others	832	11
TOTAL	7 422	100

Table 12. Area planted per apricot cultivar in South Africa in 2006 (DFPT Tree Census 2006).

Cultivar	Area planted (ha)	% of total planted area
Bulida	2 172	52
Soldonné	397	9
Supergold	308	8
Peeka	238	6
Palsteyn	349	9
Royal	209	5
Cape Bebeco	240	6
Other	185	5
TOTAL	4 100	100

Table 13. Area planted per plum cultivar in South Africa in 2006 (DFPT Tree Census 2006).

Cultivar	Area planted (ha)	% of total planted area
Songold	671	17
Laetitia	670	16
Sapphire	419	10
Pioneer	352	9
Angeleno	259	6
Fortune	225	6
Southern Belle	185	5
Sun Kiss	188	5
Flavor King	150	4
Lady Red	136	3
Souvenir	120	3
Reubennel	100	2
Santa Rosa	49	1
Harry Pickstone	55	1
Other	493	12
TOTAL	4 071	100

Table 14. Area planted per nectarine cultivar in South Africa in 2006 (DFPT Tree Census 2006).

Cultivar	Area planted (ha)	% of total planted area
Alpine	274	17
May Glo	156	10
Experimental	130	8
Margaret's Pride	101	6
Sunlite	97	6
Fantasia	85	5
Flavortop	77	5
Flamekist	68	4
August Red	53	3
Zaigina	53	3
Other	524	33
TOTAL	1 619	100

Table 15. Area planted per prune cultivar in South Africa in 2006 (DFPT Tree Census 2006).

Cultivar	Area planted (ha)	% of total planted area
Van Der Merwe	258	55
Erfdeel	124	26
Prune D' Agen	62	13
Other	28	6
TOTAL	472	100

1.5.2 Tropical and subtropical species

Citrus

Oranges are the most important citrus grouping produced in South Africa (Table 16). The Industry refers to three major groups of oranges viz. Valencias, Navels and Midseason oranges. Valencia production is the highest and makes up 40% of the total area planted to citrus in South Africa (CGA 2007). Valencias are followed by Navels (25%) and finally a small amount of Midseason oranges (2%). Within each of these groupings there are a number of cultivars. Valencia cultivars include 'Delta', 'Midnight', 'Du Roi', 'Valencia Late', 'Olinda', 'McClean' and 'Amanzi'. Navel cultivars include 'Bahianinha', 'Palmer', 'McClean', 'Washington', 'Leng', 'Royal Late', 'Newall', 'Navelina', 'Lane Late' and 'Gillimberg'. Midseason orange cultivars include 'Tomango', 'Clanor', 'Shamouti', 'Salustiana' and 'Protea'.

Grapefruit are the second most important citrus group in South Africa. Grapefruit are divided into 3 export groups based on colour, viz. Red ('Star Ruby'), White ('White Marsh Seedless') and Pink ('Rosé'/'Red Ruby'). 'Star Ruby' is the most popular export cultivar, followed by 'Marsh' and 'Rosé'. Soft citrus refers to the mandarins or easy peelers and includes 'Minneolas', 'Nules', 'Nova', 'Owari', 'Satsumas' and 'Clementines'. 'Eureka' is the most important lemon cultivar in South Africa, with minor plantings of 'Lisbon' found in some areas.

Table 16. Area planted per Citrus type in South Africa in 2006 (CGA 2006).

Citrus type	Area (ha)	% of total area
Valencias	22 756	40%
Navels	14 121	25%
Grapefruit	7803	14%
Soft Citrus	5456	10%
Lemons	5026	9%
Midseason oranges	871	2%
Pomelos	188	<1%
TOTAL	56 221	100

Avocado

There are three horticultural races or ecotypes of avocados, termed the Mexican, Guatemalan and West Indian or Antillean races. Most economically important cultivars in both subtropical and tropical areas are the result of hybridization between species. In South Africa 'Fuerte' and 'Hass' are the major cultivars planted, making up 38% and 36% of the plantings respectively (Donkin 2003). This is followed by 'Ryan' (11.8%), 'Pinkerton' (9%), 'Edranol' (5%). Minor cultivars include 'Lamb Hass', 'Reed' and 'Rinton'. The South Africa season extends from mid-March to September and due to the climatic variability in South Africa the major cultivars are available over an extended period during the season. The majority of the plantings since the early 1980's have been on *Phytophthora*-tolerant rootstocks such as 'Duke 7'. Recently a rootstock bred by Westfalia Technological Services, 'Dusa' has become commercially available which show excellent resistance to *Phytophthora*.

Mango

Mango cultivars can be divided into three groups, viz. unimproved cultivars, improved tropical cultivars and improved subtropical cultivars. The unimproved group includes South African cultivars such as 'Peach', 'Sabre', 'Kidney', 'Long Green' and the so-called Bombay types from India. This group has a very high fibre content, is susceptible to disease, and has poor shelf life and a turpentine flavour (SAMGA 2007). The improved subtropical cultivars have been imported from Brazil and the USA and the cultivars from Florida in

the USA form the basis of the South African mango industry. The most important cultivars planted in South Africa are 'Tommy Atkins' (26%), 'Sensation' (13%), 'Kent' (12%), 'Heidi' (9%), 'Keitt' (8%) and 'Zill' (8%) (1995 tree census, SAMGA). 'Tommy Atkins' and 'Zill' are early to midseason cultivars, 'Kent' and 'Heidi' are mid to late season cultivars and 'Sensation' and 'Keitt' are late season cultivars. 'Kent' and 'Keitt' are preferred on the overseas markets for their taste, followed by Tommy Atkins which has good external colour.

Macadamia

Most of the cultivars grown commercially today are selection of *Macadamia integrifolia* made at the Hawaiian Agricultural Experimental Station. These cultivars have all been given an HAES number and some have also been given a name. Some hybrids between *M. integrifolia* and *M. tetraphylla* have been selected and are commercially grown in South Africa (SAMAC 2007). SAMAC recommend that at least 3 to 4 cultivars are included in any planting. In terms of long term yield and quality '788 Pahala', '741 Mauka' and '816' are recommended cultivars. Other cultivars include 'Keaau', 'Kakea' 'Kau', 'Makai', 'Nelmak 1' and 'Nelmak 2'. More precocious varieties can be planted as inter plants in high density plantings, as they come into production earlier than the traditional cultivars and they can be thinned after 8-12 years. This includes '695 Beaumont' and '791 Fuji' (SAMAC 2007). The kernel characteristics of these cultivars are not readily acceptable and merely compensate for the years in which no crop is produced by the desirable cultivars.

Pecan

The most important cultivars in South Africa are 'Wichita', 'Choctaw', 'Barton', 'Elliot', 'Ukulinga' and 'Shoshoni' (de Villiers, 2003). Other cultivars showing promise include 'Mohawk', 'Cherokee', 'Caspiana', 'Nellis' and 'Western Schley'.

Litchis

Cultivars grown in South Africa are divided into two groups, viz. Mauritius litchis and Tao So litchis. The Mauritius group contains fruit of good quality, with a red skin colour (Cull and Lindsay 1995), and has satisfactory yields. Cultivars include 'Mauritius', 'Muzaffarpur', 'Late Large Red', 'Hazipur' 'Saharanpur' and 'Rose-Scented'. The Tai So grouping contain early litchi

cultivars that do well in the tropics but produce poorly in the subtropics. The fruit is of excellent quality and has large seeds. Cultivars in this grouping include 'Haak Yip', 'Shang Shou Huai', 'Kontand', 'Glutinous Rice' and 'Three Months Red' (Nakasone and Paull 1998).

Pineapples

Two main pineapple cultivars are produced in South Africa, 'Smooth Cayenne' and 'Queen' (Dalldorf 1990a). The majority of 'Queen' pineapples are produced in KwaZulu-Natal, whilst the majority of 'Smooth Cayenne' pineapples are produced in the Eastern Cape.

Papaya

Cultivars grown in South Africa include 'Hortus Gold', 'Honey Gold' and 'Kaapmuiden'.

Banana

Banana cultivars grown in South Africa include 'Dwarf Cavendish', 'Williams', 'Valery', 'Grand Nain', 'Chinese Cavendish', 'Lacatan' and 'Robusta' (Robinson 1996). The most important cultivar in South Africa is 'Dwarf Cavendish', followed by 'Williams'.

1.6 Soil types suitable for fruit tree orchards

Most fruit trees consist of a scion (grafted above ground shoot) and a rootstock. Through careful choice of rootstocks fruit trees can be grown in a wide range of climate and soil conditions that would normally be unfavourable for growth. Rootstocks have been selected that can tolerate poor drainage, drought, high pH or salinity, have improved cold-hardiness and are resistant to soil diseases and nematodes (Rieger 2006). The ability of fruit trees to grow on marginal soils will depend on the availability of rootstocks for those conditions and the particular fruit type. There are generally more rootstocks available for deciduous fruit trees than subtropical fruit trees, with citrus been the exception.

The soil property most limiting to fruit production is poor soil drainage, as most fruit trees are generally intolerant of water-logging and perform best on well-drained soils. Water-logging limits the oxygen available in the soil for the roots and promotes the spread of disease such as *Phytophthora* spp. In this regard soils with a limiting layer within 1-3 m of the soil surface are not ideal for fruit

production. Particular attention therefore needs to be paid to soil physical properties, as these cannot be easily changed, in comparison to soil chemical properties, such as pH which can be adjusted with liming. Fruit trees prefer lighter soils (loamy sands to silty-clay loams or clay loams). Figure 7 illustrates the generalised soil types on which fruit trees and grape vines are grown in South Africa.

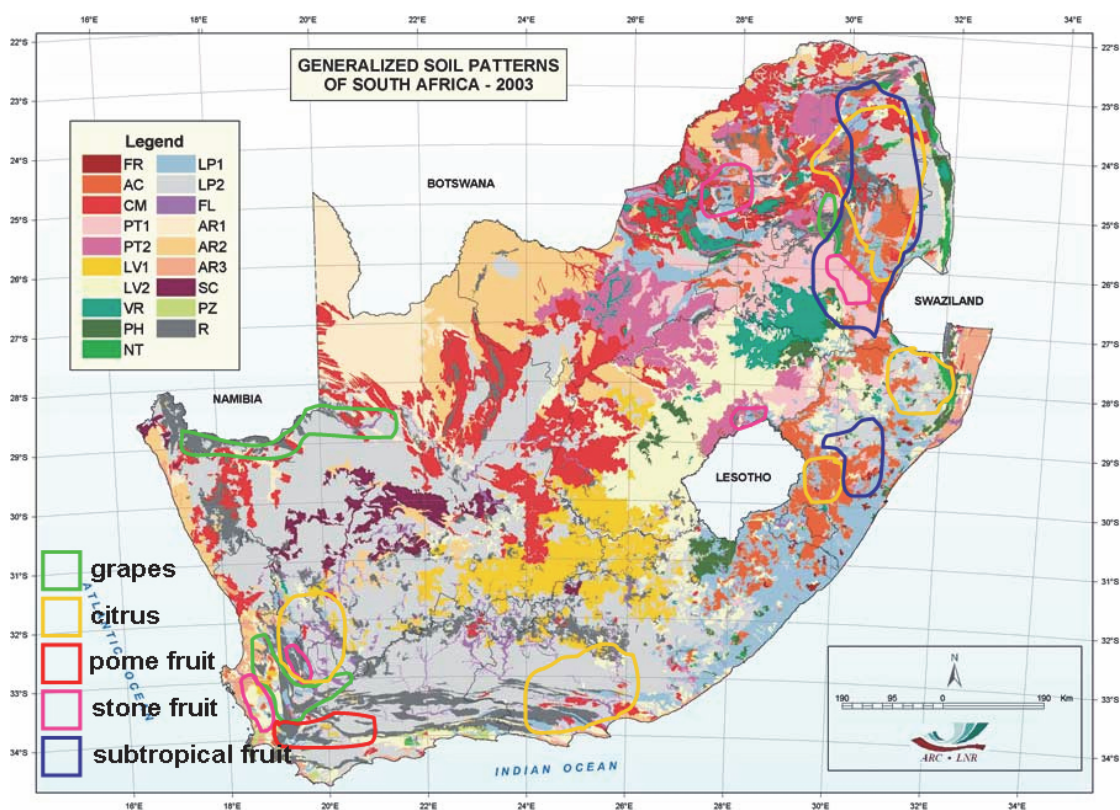


Figure 7. Distribution of fruit growing areas in South Africa according to generalised soil types (ISCW-ARC). The abbreviations of the soil types are: Ferralsols (FR), Acrisols (AC), Cambisols (CM), Plinthosols1 (PT1), Plinthosols2 (PT2), Luvisols1 (LV1), Luvisols2 (LV2), Vertisols (VR), Phaezems/Kastanozems (PH/KS), Nitisols (NT), Leptosols1 (LP1), Leptosols2 (LP2), Fluvisols (FL), Arenosols1 (AR1), Arenosols2 (AR2), Arenosols3 (AR3), Solonchaks (SC), Podzols (PZ), Regosols (R). (from http://www.esri.com/mapmuseum/mapbook_gallery/volume19/agriculture3.html).

1.6.1 Deciduous species

Apples require a deep, well-drained, loamy soil with a pH (water) of 6-7, but can be grown on a wide variety of soils world-wide due to the incredible number of rootstocks available. Pears are more tolerant of heavy, poorly

drained soils than most other fruit trees, but productivity is best on deep, well-drained loams with a pH (water) of 6-7 (Rieger 2006).

Peach trees require deep, well-drained, and loamy to moderately sandy soils. Peaches are susceptible to poor drainage and flooding stress (Rieger 2006). In areas where nematodes are problematic sandy soils should be avoided for peach cultivation. Commercial apricot production fares best on deep, fertile, well-drained soils that do not become waterlogged. Apricots are, however, more tolerant of high soil salinity and pH than most other *Prunus* spp. Plums are the most tolerant stone fruit of heavy soils and water-logging, but should ideally be cultivated on deep, well-drained soils with a pH (water) between 5.5 and 6.5. Plum rootstocks are more tolerant of drought than peach rootstocks and some rootstocks are available for high pH soils.

Grapes are adapted to a wide range of soil conditions, from high pH and salt to acidic and clayey, as a result of the range of rootstocks available. Deep, well-drained, light textured soils are best for wine grapes (Rieger 2006). Highly fertile soils are unsuitable for high quality wine production as vigour and yield need to be carefully managed. Soils for table grape production can be more fertile but should still be well-drained and light textured.

1.6.2 Tropical and subtropical species

Avocados

A large range of soils support successful avocado orchards, with varying degrees of success and management inputs. The main factors determining the suitability of soils for avocado production include root rot, inadequate soil aeration and salinity (Wolstenholme 2002). Heavy soils which drain poorly are undesirable. Even temporary soil saturation can provide an opportunity for *Phytophthora cinnamomi* infestations. Light-textured sandy soils are favoured in some areas of the world, but they are difficult to manage due to their low water holding capacity and trees can easily become stressed. Soils of intermediate texture represent the best compromise. Good soils require good aeration (low bulk density) and fast internal drainage and should have an effective depth of at least 2 m in high rainfall areas subjected to cyclonic rainfall, 1.5 m in moderate hazard situations and at least 1.0 m in semi-arid Mediterranean climates. Avocados are shallow rooted, with a maximum depth of 1.2-1.5 m in deep, well-drained soils, with the main root system developing in the 0-60 cm zone. Ideally the soil should have a moderate water holding capacity, which should be provided by high soil organic matter content (>2% in the A horizon) from decaying plant litter, including organic mulches

(Wolstenholme 2002). Every effort should be made to build up organic matter in most avocado soils.

The most typical South African avocado soil is classified as a Hutton form, a red loam to loamy clay with an orthic A-horizon grading into a red apedal B-horizon. In the cool, subtropical plateaus in 'mistbelt' environments, Inanda form soils (humic A on red apedal B) are physically excellent for avocado production (Wolstenholme and le Roux 1974). In South Africa the recommended soil pH (water) for optimal avocado cultivation (high yields and good fruit quality) is between 6.0 and 6.5 (Abercrombie 1990). The avocado is a salt-sensitive species (Whiley and Schaffer 1994), but luckily salinity problems are rare in South Africa. Avocados do not make heavy demands on soil nutrients (Lhav and Kadman 1980, Wolstenholme 1991).

Citrus

The roots of citrus trees normally grow to a depth of 1 m and spread to 2 m beyond the drip line of the tree (du Plessis 1989a). Soils for citrus cultivation should not have any limiting layer within 1 m of the soil surface as it will limit the depth to which roots can penetrate and will impact upon yield. This impermeable layer could be in the form of a solid layer of weathered rock or gravel; a tough, poorly drained clay; a sandy, mottled layer which limits water percolation and causes anaerobic conditions to develop; a layer where contraction and expansion forces can damage roots or a compacted soil layer caused by mechanical compaction or through excessive alluviation of clay particles (du Plessis 1989a). In terms of optimal water provision for citrus, a soil should be red, yellow-brown or brown in colour, have a clay content between 10 and 40% and have no clayey, mottled or structural layers within 1 m of the soil surface. Management strategies will have to be adapted if citrus is planted on soils that deviate from these ideal characteristics. Citrus is more tolerant of high or low pH and salinity than most other fruit crops. The following soils are optimally suitable for citrus production: Hutton (10-35% clay), Clovelly (10-35% clay), Fernwod (0-6% clay) and Oakleaf (10-35% clay).

Mango

Mangoes are adapted to a wide range of soils provided they are adequately drained and mildly acidic (pH 6-7.2). If aluminium in the soil is not an issue then soils with a pH of 5.5 can be used (Abercrombie 1991). The response to the soil type will largely depend on the conditions under which the mangoes are grown (Abercrombie 1991). The taproot of mango can reach a depth of 6 m but the roots responsible for nutrient uptake are found in the top 25-50 cm of the soil. Restrictive layers should therefore not fall within 75 cm of the surface as this can cause water-logging problems. Ideally soils for mango

cultivation under irrigation should be sandy loams or loams, with a clay percentage of 15-25%. Clay contents up to 50% are acceptable but if it increases above 50% then roots cannot effectively penetrate the soil and water-logging can become a problem. Conversely, mangoes grown on sandy soils exhibit poor fruit quality (Abercrombie 1991). Ideal soils for mango cultivation under irrigation include Hutton, Clovelly and Oakleaf forms (Abercrombie 1991).

Mangoes can be grown under dryland conditions when losses through evaporation and transpiration are low due to humidity, temperature and rainfall. Under such conditions the soil water retention capacity must be such that the soil can supply water during the drier months. These soils should have a depth of at least 60 cm and a clay content between 15 and 30% (Abercrombie 1991). Soils with a clay content outside of this range will not be able to supply sufficient water to the plants. Ideal soils for mango cultivation under irrigation include Hutton, Bainsvlei, Clovelly, Avalon and Oakleaf forms (Abercrombie 1991).

Macadamia

Macadamias grow on a wide variety of soil types. The main requirement is that the soil must be well drained. No restrictive layers should be present within the first meter of the soil profile. Keeping management in mind, macadamias can be grown on almost any soil type, however, management becomes more intensive on poorer soils.

Pecan

Pecans perform best in fertile, well-drained, deep soils with a loose to medium texture and 10-35% clay (de Villiers 2003). A stagnant water table within the potential rooting zone is undesirable and trees do not tolerate any water-logging. A running, non-fluctuating water level at a depth of 3-6 m is ideal (de Villiers 2003). Impermeable layers or compacted layers should not occur within 3 m of the soil surface as they will restrict root growth. Suitable soil types include Oakleaf form and Hutton, Clovelly, Griffen and Inanda forms (de Villiers 2003).

Banana

Deep, well-drained, alluvial soils are best, but bananas can tolerate a wide variety of soils. Water-logging should be avoided and thus the water table should be at least 0.6 m below the surface. If there is danger of water-logging then drainage should be facilitated or bananas should be planted on raised beds. Soils should be mildly acidic, but if pH drops to below 5.0 liming is necessary, as these conditions encourage the development of Panama

disease (*Fusarium* wilt). Bananas are considered “heavy feeders” and fertilization is heavy in order to achieve optimum yields.

Pineapples

Pineapples perform best on well-drained, sandy loams, with a pH between 4.5 and 6.5, but can be planted on almost any soil type. Rooting depth is only about 0.6 m so soil depth is not important. Drainage is, however, very important as pineapples are grown in areas with very high rainfall but they do not tolerate water-logging, as root rot and heart rot can develop. In order to avoid water-logging ridging is practiced. Highly organic soils are also suitable for pineapple production. Stable soils (e.g. Bonheim and Mayo forms), with a slope limitation of 20% are the most common pineapple growing soils in the Eastern Cape (Dalldorf 1990b).

Papaya

As a result of its shallow root distribution papaya can grow in a wide range of soils with a pH of 5.5-7.0. Papaya can be grown on soils with a depth of 60 cm and a clay content of between 5 and 40%, but a clay content between 10 and 30% is preferable with a loose, crumbly texture in the subsoil (Koen 1992). Poor drainage results in the spread of soil-borne disease and thus well-drained soils are required for papaya production. Water-logging, even for short periods, can result in lower leaf drop and can also lead to excessive fruit drop. Papaya has relatively high water requirements, implying that supplemental irrigation must be supplied, especially in the dry season. Soils forms that are suitable for growing papaya include Hutton, Clovelly, Glenrosa, Cartref, Avalon and Longlands forms (Koen 1992).

1.7 Irrigation practices

The aim of irrigation should be to obtain the maximum possible yield of marketable produce from a given amount of water supplied to the crop. In order to achieve this, a thorough understanding of the soil in the orchard and the various growth stages and water requirements of the crop are required (Orloff 2006). The three main driving variables on which irrigation decisions are based are: 1) how much water the root zone of the crop can hold, 2) how much water infiltrates into the soil and 3) how much water is the crop using? (Orloff 2006). A grower must plan irrigation according to soil water holding capacity, plant water use, prevailing weather conditions and quantified management decisions. The level of irrigation in an orchard will depend on environmental factors which drive evaporative demand and transpiration, salinity, and electrolyte composition in the soil solution, the resistance of the

soil to root penetration and water transport, soil aeration, tree hydraulic architecture (including the rootstock), and crop load (Naor 2006). Losses due to percolation, where applied water is lost below the root zone, and runoff from the soil surface must be avoided.

For long-term sustainability of perennial fruit trees it is important to safeguard against drought at all stages, but during certain stages of development each season, water may have to be managed more carefully than at other stages of growth e.g. flowering or early fruit growth. Maintaining adequate soil water conditions during water-sensitive stages of growth will have a beneficial effect on plant growth (Orloff 2006). Restricted water supply during these critical periods will negatively impact upon yield as the provision of adequate water at other stages will not compensate for the harm sustained. As soil water status and nutrition are interrelated, the provision of adequate water to plants is also required for adequate nutrient uptake (Orloff 2006). However, excessive water will leach nutrients below the active root zone, and increase the risk of root rot.

Pressures continue to increase on the available water resources of South Africa, and one of the consequences impacting irrigated agriculture is more stringent monitoring of the distribution and application of irrigated water. In a report on irrigation water measurement in South Africa van der Stoep *et al.* (2008) analysed the available sources of information on the use and management of irrigation water (e.g. AGIS atlas, WARMS and SANCID databases). A synthesis of this information revealed that approximately 1.5 million hectares of land were under irrigation in South Africa in 2007, utilising an estimated 10 468 million m³ of water per year. The majority of this land was under sprinkler systems (31%), followed by 24% under moving systems (e.g. centre pivots), 22% under micro-irrigation (micro-sprinklers, micro-sprayers and drip systems, 14% under flood systems and 9% unknown. Of the micro-irrigation systems approximately 150 000ha (i.e. 10% of irrigated land in SA) was under drip irrigation. Some of the objectives of more stringent irrigation monitoring are to improve water conservation, water demand management and water-use efficiency. Correct irrigation scheduling, (i.e. application of the correct amounts of water at the correct time to maintain optimal soil water conditions for the production of maximum yield and fruit quality) is crucial in meeting these objectives.

1.7.1 Scheduling

The aim of an efficient irrigation scheduling programme is to replenish the water deficit within the root zone minimising leaching below this depth (Fares

and Alva 2000). Excess leaching below the rooting depth will result in nutrient losses, which will increase production costs and may adversely impact upon the environment. One of the most common difficulties with irrigation systems is determining “when” to irrigate and “how much” to irrigate. Growers generally assess the crop response visually to decide when to irrigate, but this is usually too late and water stress has in all likelihood already affected tree growth and/or production adversely (Fares and Alva 2000). Growers therefore need to be able to monitor changes in either soil water status or plant water status prior to the development of any visible symptoms. Soil water therefore needs to be replenished before there is a decline in water use resulting in inadequate reserves of water for growth to be maintained. The levels of soil water at which this occurs is dependent on the soil type, the crop and management strategies. For example, Green *et al.* (2003) collected soil water and sap flow (transpiration) data from an apple orchard to support the contention that more frequent irrigation in smaller doses will result in less water percolating through the root-zone. They concluded that such an irrigation strategy would make more efficient and environmentally friendly use of water by minimising leaching losses of water and solute below the depth of the roots.

Irrigation scheduling is traditionally based on either soil water measurements (water content or water potential), where the soil water status is measured directly to determine the need for irrigation, or on soil water balance calculations, where soil water status is estimated using a water balance approach in which the change in soil water over a period is given by the difference between inputs (irrigation plus precipitation) and the losses (runoff plus drainage plus total evaporation) (Jones 2004). The water balance technique is not very accurate but has been found to be adequate over a wide range of conditions. Recently there has been a trend towards measuring the response of the plant to water deficits rather than sensing the soil water status directly (Jones 1990). A problem with soil based techniques is that many aspects of a plant’s physiology respond directly to changes in water status in the plant tissues, whether in the roots or other tissues, rather than to changes in bulk soil water status (Jones 1990). The response of a plant to a given amount of soil water is a complex function of evaporative demand. Jones (1990) therefore suggests a third approach using ‘plant “stress” sensing’ to schedule irrigation more precisely. Some of the main advantages and disadvantages of the different methods of scheduling irrigation are given (Table 17).

According to Stevens *et al.* (2005) and Stevens (2007) the choice of irrigation scheduling method adopted by the user is determined by answering the following questions; 1) how much time do I have available to use the device or

specific method and how long is needed for the interpretation of data? 2) Am I comfortable with the required level of technology? 3) What are the cost implications? 4) Is there technical and maintenance support available? 5) If soil water content is to be measured, how many units will be required to account for the variability on the farm? The various irrigation scheduling models and methods used in South Africa are illustrated (Figure 8). From a survey of 297 farmers throughout South Africa, concerning the implementation of irrigation scheduling, Stevens (2005, 2007) concluded that only 18% of this group scheduled irrigation objectively, using some form of instrumentation or model (Figure 9).

Table 17. A summary of the main classes of irrigation scheduling approaches, including their main advantages and disadvantages (Jones 2004).

Scheduling approach	Advantages	Disadvantages
I. Soil water measurements		
(a) Soil water potential (tensiometers, psychrometers, etc.)	Easy to apply in practice, can be quite precise; water content measures indicate 'how' much to apply; many commercial systems available; some sensors (especially capacitance and time domain sensors) readily automated	Soil heterogeneity requires many sensors (expensive) or extensive monitoring programme (e.g. neutron probe); selecting position that is representative of the root-zone is difficult; sensors do not generally measure water status at the root surface (which depends on evaporative demand)
(b) Soil water content (gravimetric; capacitance/TDR; neutron probe)		
II. Soil water balance calculations (require estimate of evaporation and rainfall)	Easy to apply in principle; indicate 'how' much water to apply	Not as accurate as direct measurement; need accurate local estimates of precipitation/runoff; total evaporation estimates require good estimates of crop coefficients (which depend on crop development, rooting depth, etc.); errors are cumulative, so regular calibration needed
III. Plant "stress" sensing (Includes both water status measurement and plant response measurement)	Measures the plant stress response directly; integrates environmental effects; potentially very sensitive	In general, does not indicate 'how much' water to apply; calibration required to determine 'control thresholds'; still largely at research/developmental stage and little used yet for routine agronomy (except thermal sensing in some situations)
(a) Tissue water status	Argued that leaf water status is the most appropriate measure for many physiological processes (e.g. photosynthesis) this is generally erroneous (ignore root-to-shoot signalling)	All measurements subject to homeostatic regulation (especially leaf water status), therefore not sensitive (isohydric plants); sensitive to environmental conditions that can lead to short-term fluctuations greater than treatment differences

(i) Visible wilting	Easy to detect		Not precise; yield reduction often occurs before visible symptoms; hard to automate
(ii) Pressure chamber (ψ)	Widely accepted reference technique; most useful if estimating stem water potential (SWP), using either bagged leaves or suckers		Slow and labour intensive (therefore expensive especially for predawn measurements); unsuitable for automation
(iii) Psychrometer (ψ)	Valuable, thermodynamically based measure of plant water status; can be automated		Requires sophisticated equipment and a high level of technical skill, yet still unreliable in the long run
(iv) Tissue water content (RWC, leaf thickness [γ - or β -ray thickness sensors], fruit or stem diameter]	Changes in tissue water content are easier to measure and automate than water potential measurements; relative water content (RWC) more directly related to physiological function than is total water potential in many cases; commercial micromorphometric sensors available		Instrumentation generally complex or expensive, so difficult to get adequate replication; water content measures (and diameter changes) subject to same problem as other water status measures; leaf thickness sensitivity limited by lateral shrinkage
(v) Pressure probes	Can measure the pressure component of water potential which is the driving force for xylem flow and much cell function (e.g. growth)		Only suitable for experimental or laboratory systems
(vi) Xylem cavitation	Can be sensitive to increasing water stress		Cavitation frequently depends on stress prehistory; cavitation-water status curve shows hysteresis, with most cavitations occurring during drying, so cannot indicate successful rehydration
(b) Physiological responses	Potentially more sensitive than measures of tissue (especially leaf) water status		Often require sophisticated or complex equipment; require calibration to determine 'control thresholds'
(i) Stomatal conductance	Generally a very sensitive response, except in some anisohydric species		Large leaf-to-leaf variation requires much replication for reliable data

-Porometer	Accurate: the benchmark for research studies	Labour intensive so not suitable for commercial application; not readily automated (some attempts have been made)
-Thermal sensing	Can be used remotely: capable of scaling up to large areas of a crop (especially with imaging); imaging effectively averages leaves; simple thermometers cheap and portable; well suited for monitoring purposes	Canopy temperature is affected by environmental conditions and stomatal aperture, so needs calibration (e.g. by using wet and dry reference surfaces)
-Sap flow sensors	Sensitive	Only indirectly estimates changes in conductance, as flow is also very dependent on atmospheric conditions; requires complex instrumentation and technical expertise; needs calibration for each tree and for definition of irrigation control thresholds
(ii) Growth rates	Probably the most sensitive indicator of water deficit stress	Instrumentation delicate and often expensive

IRRIGATION SCHEDULING METHODS

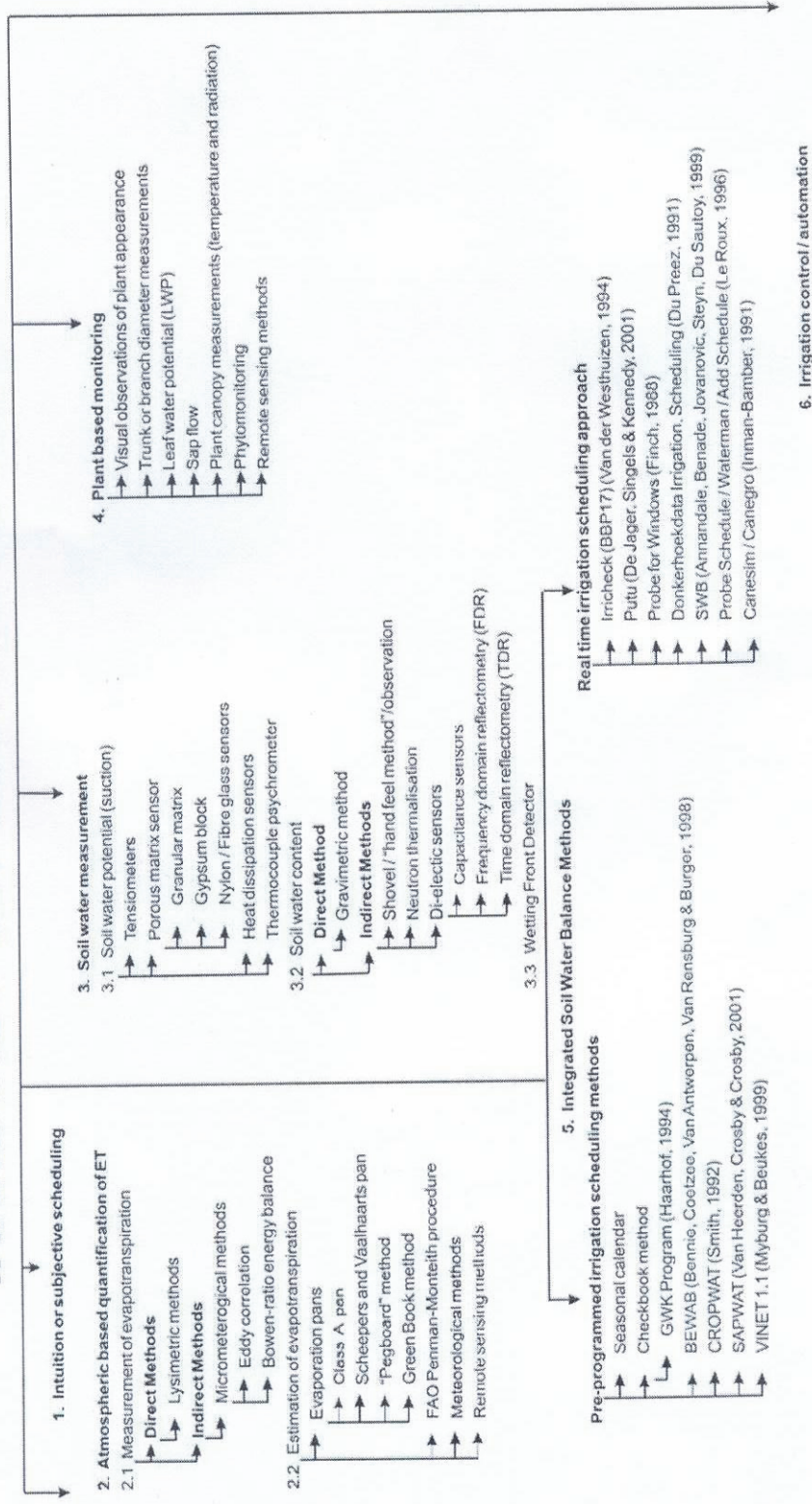


Figure 8. Classification of irrigation scheduling models and methods used in South Africa (Stevens 2007).

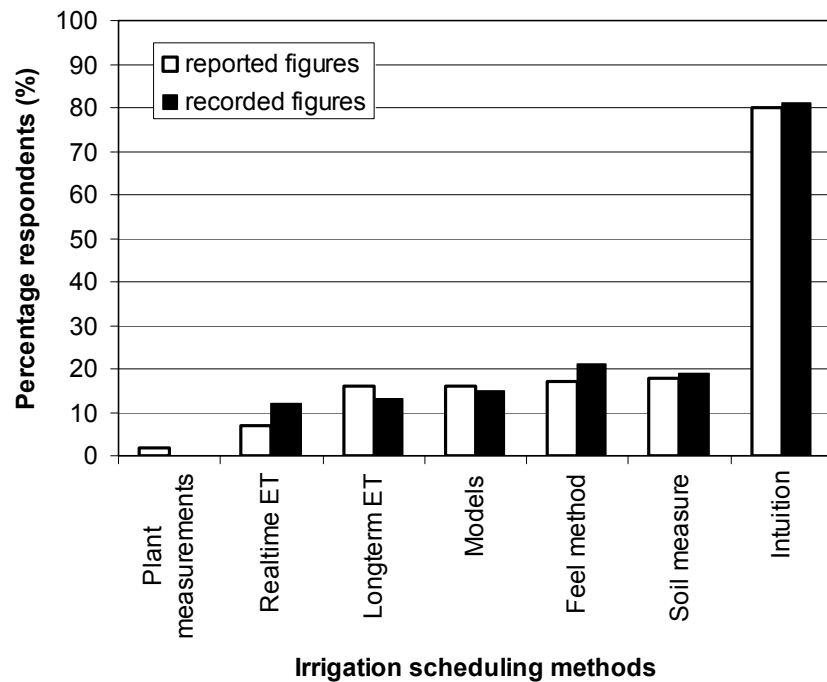


Figure 9. The implementation of different irrigation scheduling methods by farmers surveyed by Stevens (2007). Recorded figures from the survey and reported figures by representative respondent, supported by consensus of a smaller reference group are shown (Stevens, 2007).

From Figure 9, it is evident that farmers still rely heavily on intuition as a means of scheduling irrigation, which includes fixed or semi-fixed irrigation calendars based on intuition, local experience, knowledge, observation and feeling. Irrigation farmers on the whole in South Africa are therefore, in all likelihood, not scheduling irrigation precisely enough to maximise production per unit water, especially when taking into account that South Africa is a water scarce country.

Soil water measurements and soil water balance calculations

Through soil water monitoring the rate of soil water depletion can be measured and predictions on when and how much water to be applied can be calculated (Orloff 2006). Monitoring soil water status during and after irrigation is important in order to optimise irrigation and fertilizer management (Fares and Alva 2000). When positioning monitoring sites it is important to allow for crop and soil variations. In this regard, positioning soil monitoring site within the average within the average soil type will reduce the risk of better soils being under watered and worse soils being over-irrigated, which will lead to water-logging. Monitoring sites in relation to the crop and the irrigation system should take representative measurements of both plant water usage and wetting from the irrigation system (Orloff 2006). Plant spacing, crop type and soil type all need to be taken into consideration. Under micro-sprinkler or drip

irrigation systems soil measurements provide limited quantitative data due to partial and uneven distribution of water in the soil. The depth and the number of sensors used must be carefully considered in order to differentiate between water use and drainage. At least three depths in the soil profile should be monitored (Orloff 2006). One sensor should be placed within the root zone of the crop and one below the root zone. The “effective” amount of rainfall or irrigation must be measured which is defined as that which has infiltrated into the root zone of the crop and is available to the crop.

Tensiometers are one of the cheapest and easiest instruments for measuring the soil water status. These instruments measure soil suction which is the tension that builds up in the water column in the instrument as a result of the flow of water out into the soil (Outspan 1997). This tension is the same as that which the plant must exercise to extract water from the soil. This tension varies with soil type and will thus not always measure the available water for the plant, especially in heavy soils. Tensiometers are therefore better suited for use on sandy soils, where they monitor most of the available water. Typical guidelines for the use of tensiometers for irrigation scheduling, suggest that when a tensiometer is functioning correctly it will give a reading between -5 and -20 kPa at field capacity in most soils (Outspan 1997). As the soil dries out water tension in the soil increases until it reaches a critical point where water is no longer readily available to the plants and irrigation must be applied. Typically this will lie between -30 and -70 kPa, depending on the soil type. In this situation the volume of irrigation remains the same, just the time between irrigation varies. More than one tensiometer needs to be placed in an orchard at varying depths and readings should be taken daily. The problem with tensiometers is that they measure a relatively small quantity of soil.

Time domain reflectometry (TDR) tensiometers and capacitance probes can also be used to measure soil water content before making irrigation decisions. Capacitance probes measure the dielectric constant of the soil-water-air medium (Fares and Alva 2000) and requires calibration. Capacitance probe measurements are influenced by the soil type and the bulk density of the soil (Kuraz and Matousek 1977, Bell *et al.*, 1987). Fares and Alva (2000) demonstrated that it was possible to maintain the water storage in a sandy soil above the corresponding set points for citrus based on capacitance probe readings.

Growers also make use of class A pans and various crop coefficients to calculate irrigation requirements. Application of the Class A pan evaporation figures in scheduling is based on a close relationship between total evaporation and the pan evaporation figure. Total evaporation of a specific crop may thus be calculated by multiplying pan evaporation by a unique crop

factor. This was the approach used in the development of the original “Green Books” for estimated irrigation requirements of crops in South Africa (Green, 1985a,b). The crop factor will change depending on the crop species, growth stage of the crop, time of year and crop load. The volume of the root reservoir also needs to be calculated in order to determine when irrigation needs to occur (Outspan 1997). The main disadvantage of this method is that the crop factor is based on averages. These crop coefficients are also compiled for mature trees and thus these need to be adjusted for immature trees which have a smaller canopy size. It also does not take into account the soil water holding capacity, effectiveness of irrigation or rain events, depth of water infiltration, depth of plant water extraction and effects of plant health on water usage. Studies in the Levubu area indicated that a low crop factor of 0.3 was adequate for pineapples in a “normal” year (du Plessis 1989b). This implies that for every 100 mm evaporated from a Class A pan 30 mm of water must be applied. Traditionally irrigation scheduling in citrus has been done according to the FAO method, using crop coefficients and evaporation from Class A pans (Doorenbos and Pruitt 1977, Castel 1997). This method has some uncertainties as citrus tree water use changes depending on light interception (Consoli *et al.*, 2006b) or crop load (Syvertsen *et al.*, 2003, Yonemoto *et al.*, 2004). Water budgets can also be drawn up and soil water monitored with tensiometers (Falivene *et al.*, 2006).

Plant based measurements

In order to accurately schedule irrigation based on plant-based measurements it is important to consider what measures would be most appropriate. This could include direct measurement of the plant water status as well as the measurement of a number of processes known to respond sensitively to changes in plant water status (Jones 2004). The choice of which plant-based measurement to use will depend on the sensitivity of the parameter to water deficits. The use of any plant-based measurement for irrigation scheduling requires the definition of threshold values, beyond which irrigation is necessary. These references are commonly determined for plants growing under non-limiting soil water supply (Feres and Goldhamer 2003). The behaviour of these reference values need to be evaluated over changing environmental conditions for the development and validation of the method. A limitation of plant-based measurements is that they generally indicate when to irrigate and not how much to apply.

The direct measure of plant water status should give a good indication of the irrigation requirements of a crop, but it should be kept in mind that plant water status is subject to some physiological control. The question remains as to where these measurements should be made. Plants tend to try and minimise the changes in leaf and shoot water status as soils dry or as evaporative

demand increases (Bates and Hall 1981; Jones 1983). Plants that can maintain a stable leaf water status over a wide range of evaporative demands are referred to as 'isohydric' plants and those that have less effective control of leaf water status are termed 'anisohydric' (Stocker 1956). Plants are able to stabilise leaf water status in the long term through changes in leaf area and root extension and in the short term through changes in leaf angle, stomatal conductance and hydraulic properties of the transport system (Jones 2004). By accounting for diurnal and environmental variation, leaf water potential can provide a sensitive index for irrigation control (Peretz *et al.*, 1984). The measurement of stem water potential (SWP) is proposed to be a more robust measurement of plant water status than leaf water potential and is reported to eliminate some of the variability encountered with leaf water potential measurements (McCutchan and Shackel, 1992) and give a better indication of soil water status. Midday SWP has been proposed as the standard measurement of water status in fruit trees for irrigation management (Shackel *et al.*, 1997, Naor, 2000). Stomatal conductances can be misleading in long-term experiments but in the short term stomata are a particularly sensitive early indicator of water deficits (Jones, 2004). This is partly the result of root-to-shoot signalling playing a major role in the control of stomata aperture (Davies and Zhang, 1991) and not the leaf water status.

Importantly none of these methods are well adapted for automation of irrigation scheduling due to the difficulties of measurement of the required variables. In fact, the favoured way to use plant water status is as an indicator of soil water status, which itself can be measured directly. Indirect methods for the estimation of plant water status have also been developed and include leaf thickness, stem and fruit diameter and γ -ray attenuation.

Maximum daily shrinkage (MDS) of almond tree stems was shown to be a more sensitive approach for automated irrigation scheduling than was the use of stem water potential (Fereres and Goldhamer 2003), while differences in maximum trunk diameter were useful in olive (Moriani and Fereres, 2002). This is based on the principle that in the morning as stomata open, gas exchange between the leaves and the environment commences, and the leaves partially dehydrate. As a result the transpiration stream begins to flow to replace this lost water and the tree stem shrinks (Kozlowski, 1976). Conversely, in the afternoon as stomata close and the transpiration decreases, water uptake by the roots exceeds the tree water loss and the stem starts to swell (Kozlowski, 1976). The use of such dendrometry or micromorphometric techniques have been developed into a number of successful commercial irrigation scheduling systems (e.g. 'Pepista 4000', Delta International, Montfavet, France) and are usually applied to changes in stem diameter (Jones 2004). Variations in stem/trunk diameter have generally

been found to be more sensitive indication of irrigation needs than changes in fruit diameter (Sellés and Berger, 1990) and can therefore be used to better control the deficit irrigation practices and ensure that severe water stress is avoided (Velez *et al.*, 2007). Through deficit irrigation scheduling using MDS Velez *et al.* (2007) were able to demonstrate small water savings without a reduction in yield. MDS will vary according to environmental conditions and this needs to be taken into account when using it as an irrigation scheduling tool. Velez *et al.* (2007) suggest that the environmental variable best related to MDS variation will change with each species, climatic or cultural conditions. This is of practical importance and could hinder widespread implementation of this technique, as reference equations will have to be derived for each specific location, and possibly for each year.

Sap-flow measurements for irrigation scheduling have been tested in a wide range of crops including grapevine (Eastham and Gray, 1998; Ginestar *et al.*, 1998a,b) fruit and olive trees (Ameglio *et al.*, 1998; Fernandez *et al.*, 2001; Giorio and Giorio, 2003; Remorini and Massai, 2003; Fernandez *et al.*, 2008; Steppe *et al.*, 2008) and some greenhouse crops (Ehret *et al.*, 2001). Although sap flow rates are expected to be sensitive to water deficits and therefore stomatal closure, it is important to note that changes in transpiration can be influenced by environmental factors such as humidity and thus changes in sap flow can occur without changes in stomatal opening (Jones, 2004). 'Control thresholds' may be acquired by means of regular calibration measurements, especially for larger trees. In terms of precision control changes in sap flow tend to lag behind changes in transpiration rate owing to the hydraulic capacitance of the stem and other plant tissues (Wronski *et al.*, 1985). It is possible to develop an irrigation scheduling algorithm that is based on the diurnal patterns of sap flow, with midday reductions indicative of a developing water stress. It should be kept in mind that diurnal fluctuations in environmental conditions can mimic such changes (Jones, 2004). This method is well adapted for automation and hence for potential automation of irrigation systems, but it can be a little difficult to correct the control points for any crop (Jones, 2004). Several physiological variables, such as diurnal fluctuations in fruit and tree diameter (Kalmer and Lahav, 1977), leaf thickness (Schroeder and Wieland, 1956; Sharon, 1999), leaf water potential (Bower *et al.*, 1977; Sterne *et al.*, 1977) and sap flow velocity (Cantuarias-Aviles, 1995) have been used with varying degrees of success to control or adjust irrigation scheduling for avocado.

As already mentioned stomatal conductance is particularly sensitive to changes in a plant's water status and may therefore provide a good indication of a plant's irrigation needs (Jones, 2004). Although stomatal conductance can be measured accurately using diffusion porometers, measurements are

labour intensive and unsuitable for automation. Recent developments for detecting plant stress have involved monitoring stomatal closure through thermal sensing of leaves with infrared thermometers as leaf temperature rises as plants become water stressed and close their stomata (Raschke, 1960). A method to account for the fluctuations in leaf temperature as a result of radiation and wind is to compare leaf temperature with air temperature and integrate the difference (Jones 2004), where a significant elevation of leaf temperature above air temperature is evident of stomatal closure and water deficit stress. Shortfalls in this technique can occur in humid, cloudy environments. It has therefore been used successfully for irrigation scheduling in many arid environments (Jackson, 1982; Stockle and Dugas, 1992; Martin *et al.*, 1994). The recent introduction of thermal imagery has allowed advances in thermal sensing for plant stress detection and irrigation (Jones, 1999; Jones *et al.*, 2002).

Although plant-based measurements for irrigation scheduling have several advantages, including a greater relevance to plant functioning than soil-based measurements, they have been offset by a number of practical difficulties of implementation which have so far limited the development of commercially successful systems.

Water budgeting (Irrigation scheduling for Fruit Crops)

Irrigation can be scheduled according to a water budget approach and has the following advantages: 1) no equipment requirements, (2) accuracy, (3) simplicity of use, and (4) flexibility allowing easy adaptation to use in other crops (Tan, 2007). The water budget approach is slightly different for high-volume sprinkler-irrigated orchards than for those with low-volume drip or micro-sprinklers. For sprinkler irrigation the grower must first estimate the amount of available water in the root zone. This is achieved by multiplying the appropriate available water value by the average rooting depth (see examples in Table 18 and Table 19).

Table 18. Ranges in available water capacity and intake rate for various soil textures (Tan 2007).

Soil Texture	Available water capacity (mm of water cm ⁻¹ soil)		Intake rate (mm h ⁻¹)	
	Range	Average	Range	Average
Sand	0.5-0.8	0.65	12-20	16.0
Loamy sand	0.7-1.0	0.85	7-12	9.5
Sandy loam	0.9-1.2	1.05	7-12	9.5
Loam	1.3-1.7	1.50	7-12	9.5
Silt loam	1.4-1.7	1.55	4-7	5.5
Silty clay loam	1.5-2.0	1.75	4-7	5.5
Clay Loam	1.5-1.8	1.62	4-7	5.5
Clay	1.5-1.7	1.60	2-5	3.5

Secondly, the allowable soil water depletion in the root zone (about 50%) should be estimated. This is the amount of water in the soil profile that can be extracted without causing adverse effects on tree growth, yield and quality and is calculated by multiplying available water by 50%. Thirdly, the water use rate of the various fruit crops needs to be calculated. This will vary according to site and time of year. Through the use of crop coefficients and the average weekly or average daily maximum total evaporation, average daily water use rates can be calculated. Fourthly, decisions must be made as to when to irrigate. This should be calculated after a thorough wetting of the soil and the amount of available water in the crop root zone must be determined by direct measurement. Deciding when to irrigate is then determined by subtracting daily water use of crops from total available water in the root zone until the soil water has been reduced to the allowable depletion level. The amount of irrigation to apply is calculated by dividing the allowable soil water depletion by the irrigation efficiency. Irrigation efficiency depends on the size and uniformity of fields, the climatic conditions and the manner in which the irrigation is delivered as water may be lost through deep percolation, runoff and evaporation. The duration of the water application depends on the amount of water to be applied and the water intake rate of the soil, as you do not want runoff to occur.

Table 19. Irrigation depths for various crops (Tan 2007).

Crops	Depth to irrigate (cm)
Apples	90
Cherries	60
Grapes	90
Pears	60
Raspberries	60
Strawberries	30

For low-volume drip or micro-sprinkler systems the daily water use rate by trees needs to be calculated as $\text{L tree}^{-1} \text{ day}^{-1}$. The frequency of drip irrigation is related to system design, tree daily water requirements, number of emitters per tree and the emitter flow rate. Low volume drip systems operate daily and maintain optimum water conditions in the root zone thereby preventing water stress. Micro-sprinklers on the other hand wet larger areas of the soil surface and meet the soils water requirements every 2-3 days, allowing greater flexibility in irrigation. Irrigation frequency is equivalent to total usable water in the soil profile divided by the daily water use of the tree. Total usable water is a function of total usable water per meter of soil depth, total soil root zone reservoir and area shaded per hectare (Tan 2007). Soil type will determine the number, spacing and flow rate of emitters. In sandy soils emitters will have to be placed closer to the trees while in clay soils will require a low emitter flow rate to allow for slower infiltration. The actual irrigation amount will be calculated by dividing the water usage of each fruit tree ($\text{L tree}^{-1} \text{ day}^{-1}$) with the application efficiency and multiplying this by the irrigation frequency. The duration of the water application will depend on the amount of water to be applied and the irrigation application rate, which is calculated based on discharge per emitter and number of emitters per tree.

1.7.2 Types of irrigation

Common irrigation methods include traditional flood systems, such as furrows, borders and level basins; pressurised systems, such as sprinklers and microsprays and low pressure drip systems (Bryla *et al.* 2005). Soil physical properties will largely determine the suitability of the various irrigation systems in an orchard. Using a flood system irrigation is applied 2-4 times per month, depending on weather and water availability; whilst sprinkler and micro sprinkler systems apply irrigation 2-3 times a week and finally drip systems are used daily to apply water. Growth and production of young peach trees

have been found to be significantly affected by irrigation method (Bryla *et al.* 2003). Trees irrigated with drip or subsurface drip were larger and produced better yields than those irrigated by furrows or microsprays. These differences were attributed to irrigation efficiency, irrigation frequency and water placement within each system. Similar results were obtained in a subsequent study using mature peach trees (Bryla *et al.* 2005). Surface and subsurface drip increased average fruit size, reduced the number of unmarketable fruit and improved marketable yield relative to traditional furrow or microspray irrigation.

Orchards irrigated with inefficient systems will require more water to maintain a favourable water status and sustain good yields, than an orchard irrigated with an efficient system, where little water is lost through percolation, evaporation, runoff or through the action of wind. Micro- and drip irrigation deliver irrigation more efficiently than sprinklers. The efficiency of micro-sprinklers is about 90-100%, whilst drippers are almost 100% efficient and can reduce water stress between irrigations (Tan 2007). Micro-sprinklers have the potential to limit chemical and water loading to deep soil layers and groundwater, while sustaining agricultural yield and fruit quality on a variety of soils. The placement of the water is another critical component of efficient irrigation and a concern with drip irrigation is that the limited wetted soil volumes will induce tree water deficits. Different types of irrigation will result in increased yields in different fruit types e.g. although drippers proved unfavourable in a grapefruit orchard (Zekri and Parsons 1988), they maximised production in seedling peach trees (Tan and Buttery 1982). In general, drip irrigation is well suited to high-density plantings, especially in medium to heavy textured soils with high water holding capacity (Swietlik 1992) but may be unsuitable to coarser soils due to poor lateral movement of water from drippers. Stassen and Davie (1996a) advise that irrigation should only wet the drip area of the tree and thus a micro- or drip system that succeeds in wetting a continuous area in the tree row effectively is recommended.

1.7.3 Irrigation strategies

Deficit irrigation

Controlled stress through irrigation can be applied to inhibit growth and stimulate reproductive development (Stassen and Davie 1996b). The regulation of a slight plant water deficit can improve the partitioning of carbon to reproductive structures and control excessive vegetative growth (Chalmers *et al.* 1981). This method of irrigation has been termed 'regulated deficit irrigation' (RDI) by Chalmers *et al.* (1986). This requires accurate soil water

determination and applying small quantities on a regular basis, such that soil water can be maintained within a narrow tolerance in order not to lose the effect of a slight water deficit. Partial root-zone drying (PRD) has also been employed to achieve the same level of control and involves alternating supply of water to different parts of the root system (Dry and Loveys 1998, Stoll *et al.* 2000b). Irrigation is less critical with this method than RDI as the plant can always obtain water from the well-watered roots and the growing side provides a signal to modify growth and stomatal aperture (Stoll *et al.* 2000a). Great success with these methods has been achieved with fruit crops where the part of value is the reproductive structure (Jones 2004). Precision irrigation systems, required for these scheduling strategies, require a sensing system that determined irrigation needs in real time, or at frequent intervals, which rules out manual monitoring programmes and indicates a need for automated monitoring systems (Jones 2004).

Precise measurement of plant water status can be used to schedule deficit irrigation avoiding severe water stress which is detrimental to yield and fruit quality. MDS is proposed to be a reliable indicator of plant water stress in citrus (Ginestar and Castel 1996b, Ortuño *et al.* 2006).

Water stress is also applied to some fruit crops close to harvest to concentrate sugars in fruits by reducing the water content of fruit. As a result fruit quality is enhanced. This technique is applied in apples, wine grapes and oranges (Outspan 1997, Orloff 2006). It is not very effective on heavy soils and in areas where rainfall occurs during critical phenological events.

Irrigation based on phenological cycles

The impact of water stress on plant growth will vary substantially depending on the crop growth stage. Fruit trees have different water requirements throughout the growing season and the sensitivity of the tree to water deficit stresses will vary substantially depending on the growth stage. There are also crucial phenological events where water stress must be avoided, these include fruit initiation, fruit growth and root growth. An example of the varying water requirements of a fruit tree during the season are given for avocado (Figure 10).

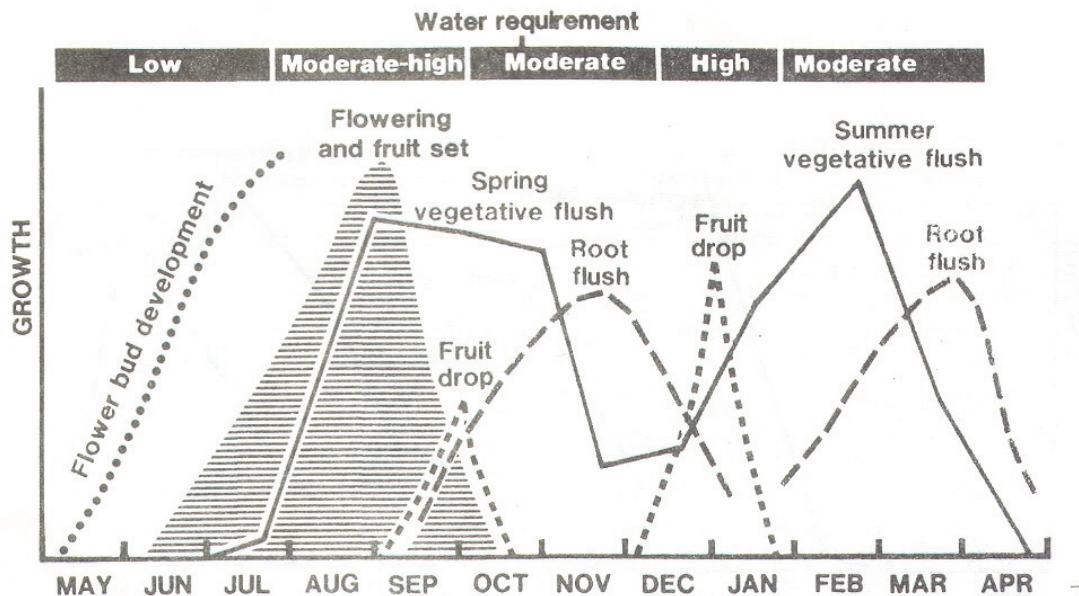


Figure 10. Periods of low, moderate and high water demand by an avocado tree for the various growth processes throughout the year in the Southern Hemisphere (Whiley et al., 1988a).

In avocado adequate irrigation is required during flowering and early fruit development (Lahav and Whiley 2002). Management of water during flowering can be critical for fruit set due to increased water loss during flowering (Whiley *et al.*, 1988b). Irrigation, however, must never decrease aeration and cool soil temperatures during spring as this will have an adverse effect on tree growth and productivity. The second critical period for irrigation is the rapid fruit growth phase. Effective irrigation management during this time can reduce fruit drop and increase final fruit size (Bower, 1985; Whiley *et al.*, 1988a; Wolstenholme *et al.*, 1990) by preventing tree stress. To ensure maximum fruit size during the rapid growth phase in summer, irrigation intervals should be shortened, however, in autumn when fruit growth is slow there is no advantage to shortening the irrigation intervals (Lahav and Kalmar, 1983). Reducing irrigation in autumn can enhance cold hardiness, by avoiding late growth flushes, which are extremely sensitive to frost. Surface irrigation during winter can increase the ability of soil to accumulate heat during the day and radiate it back to the canopy at night. The normal irrigation frequencies for avocado in hot climates are 7-12 days for under-tree sprinkling, 2-7 days for mini-sprinklers and 1-3 days for drip irrigation (Lahav and Whiley, 2002). It takes 4-6 years to achieve full ground cover (leaf area index) and maximum total evaporation for a newly planted avocado orchard, depending on tree spacing and location (Lahav and Whiley, 2002). The amount of water applied during establishment should take tree size into account. According to Gustafson *et al.* (1979) a 4-year old avocado tree will require a maximum of 70 L day^{-1} if irrigated by drip/trickle system. Critical phenological events where water stress should be avoided are similar for citrus and avocado (Falivene *et*

al., 2006). Citrus trees require water all year round, but 54% of the annual water use occurs between November and February (Figure 11), during the period of fruit growth and development (Falivene *et al.*, 2006).

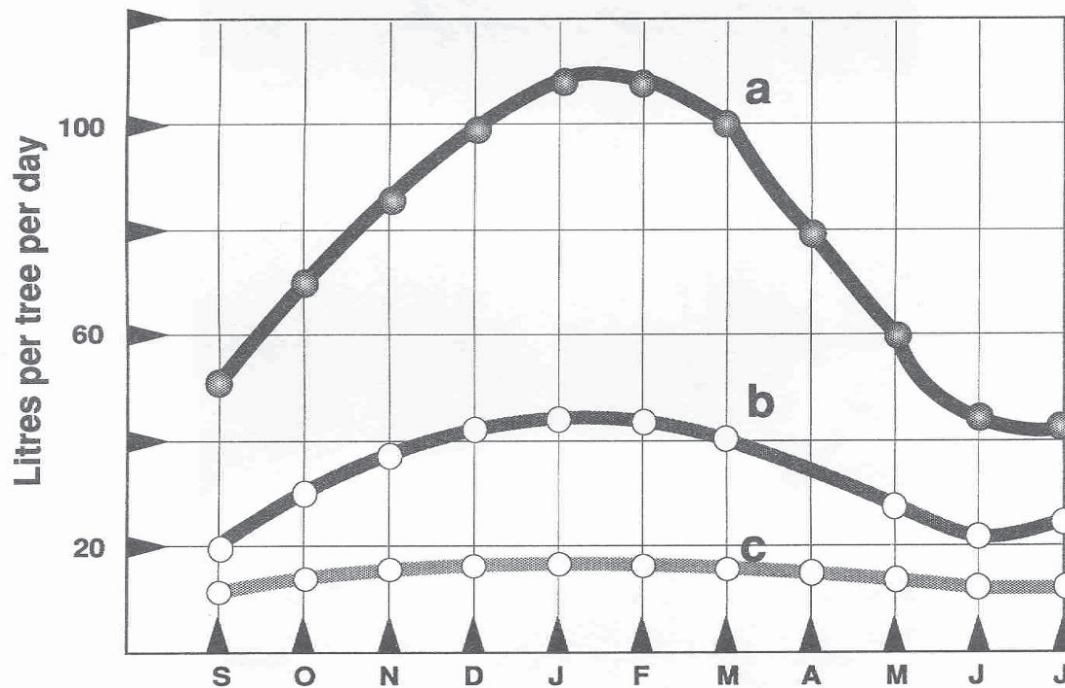


Figure 1: Average monthly water consumption of different size citrus trees (du Plessis, ITSC, 1989)

a = Mature - Soil surface area of leaf canopy 18 m²
b = 8 year old - Soil surface area of leaf canopy 7,5 m²
c = 3 year old - Soil surface area of leaf canopy 2,5 m²

Figure 11. Average monthly water consumption of different sized citrus trees (Outspan 1997).

Water availability strongly influences flowering and fruit set and can affect fruit drop, fruit size, yield, internal fruit quality characteristics and canopy development. Water stress during flowering and fruit set will result in the reduction of final fruit numbers through excessive fruit drop and soil water should not be allowed to fall below 33% depletion of available soil water (Parsons, 1989). From January to August soil water can be depleted by 50-67% prior to irrigation (Swajstrla *et al.*, 1988). The final size of fruit will be reduced if water stress occurs during the cell division phase of fruit development and this effect is enhanced if it occurs during the cell enlargement phase of fruit development, which is the linear phase of fruit growth (Falivene *et al.*, 2006, Hutton *et al.*, 2007). The period of December fruit drop is less sensitive to water restrictions, provided water applications are returned to the full amount sufficiently before harvest in order to allow for compensation in fruit growth (Cohen and Goell, 1988). Restricting soil water during flower bud initiation can ensure satisfactory flower bud initiation. This has been applied particularly in lemons and for decades in Sicily in particular.

In mango rapid growth needs to be encouraged in non-bearing trees and thus frequent, light applications of water are required to prevent over saturation of the root zone (Wittwer, 1991). As young trees do not have a well-developed root system, the root volume should only be wetted to field capacity. In bearing trees, fruit bud differentiation occurs in winter and is accompanied by an accumulation of carbohydrates in the tree. Soil water status should be reduced during this period so as to prevent excessive vegetative growth which will deplete the tree of the accumulated reserves (Wittwer, 1991). Good flower formation is promoted by allowing the soil to dry out for 2 to 3 months prior to flowering (Abercrombie, 1991). Excess water in autumn can retard flowering, as a result of excessive vegetative growth which competes with reproductive growth. Water deficit stress is also used in citrus, especially lemons, to induce flowering (Outspan, 1997). Irrigation during early fruit development is essential to prevent fruit drop and promote the development of young fruit. Supplemental irrigation from fruit-set to ripening improves fruit size and quality considerably (Abercrombie, 1991).

A major difference between scheduling irrigation for deciduous fruit and subtropical and tropical fruit is that during winter deciduous plants are leafless and thus the transpiration rate is low. Over winter subtropical and tropical fruit trees still have leaves and thus transpiration will be higher in these crops over winter, especially in the warmer growing areas. Canopy conductance in deciduous fruit trees during the dormant season is zero and they are not irrigated despite the fact that there is still evaporation from the soil (Naor, 2006). Crop coefficients for deciduous fruit trees increase with increasing foliage coverage and varies according to seasonal changes in canopy conductance that result from changes in tree-water relations and according to crop level (Naor, 2006). A corollary of this is that critical periods of water stress will differ between these two groupings of fruit and as a result irrigation scheduling with phenological cycles will differ. The following processes in deciduous fruit are sensitive to water stress: (1) reproductive cell division, (2) fruit drop, (3) canopy growth, (4) flower bud differentiation and development (starts in midsummer and continues through the growing season) (Naor, 2006). Critical water requirements for evergreen species (e.g. citrus and avocados) differ slightly as flowers are formed after winter cold and during budbreak there is a large leaf area. As a result, flowering and fruit set is a period of critical water requirement in these trees, whilst the water demand during flowering in deciduous trees is not high due to the lack of leaves and lower water demand at this point in time (Kotzé, 1991).

1.8 Appropriate water use measurement methodologies

There are a host of measurement methodologies for estimating ET and its various components. Rana and Katerji (2000) provide an excellent overview of all the methods, together with an analysis of their respective underlying principles, time and space scales of application, accuracy, potential problems and suitability for use in arid and semi-arid environments. A number of these methodologies are specifically suited to measurements of whole tree water use, including weighing lysimeters, large-tree potometers, ventilated chambers, radioisotopes, stable isotopes and an array of heat balance/heat dissipation methods (Wullschleger *et al.*, 1998). These authors note that the thermal techniques that made many of these estimates possible have gained widespread acceptance, and energy-balance, heat dissipation and heat-pulse systems are now routinely used with leaf-level measurements to investigate the relative importance of stomatal and boundary layer conductances in controlling canopy transpiration, whole-tree hydraulic conductance, coordinated control of whole-plant water transport, movement of water to and from sapwood storage, and whole-plant vulnerability of water transport to xylem cavitation.

Techniques for estimating whole-tree water use complement existing approaches to calculating catchment water balance and provide the forest hydrologist with another tool for managing water resources (Wullschleger *et al.*, 1998). Of the range of techniques listed above, the three most popular methods for estimating total evaporation in a cultivated horticultural field are the soil water balance method, the micrometeorological method, and the method of combining measurements of soil evaporation with plant transpiration. These are briefly reviewed below.

1.8.1 Soil water balance method

This method essentially calculates total evaporation (ET) as the residual term within a water balance equation. When applied to the soil, the complete equation is:

$$P + I - R - D - E - T = \pm[\Delta S] \quad (1)$$

where P is precipitation, I is irrigation, W is contribution from water table upward, R is surface runoff, D is drainage and ΔS is soil water storage in the soil layer (or Plant Available Water, PAW) where the roots are active, to supply water to the plant (Figure 12). Units for all the terms are millimetres per unit time.

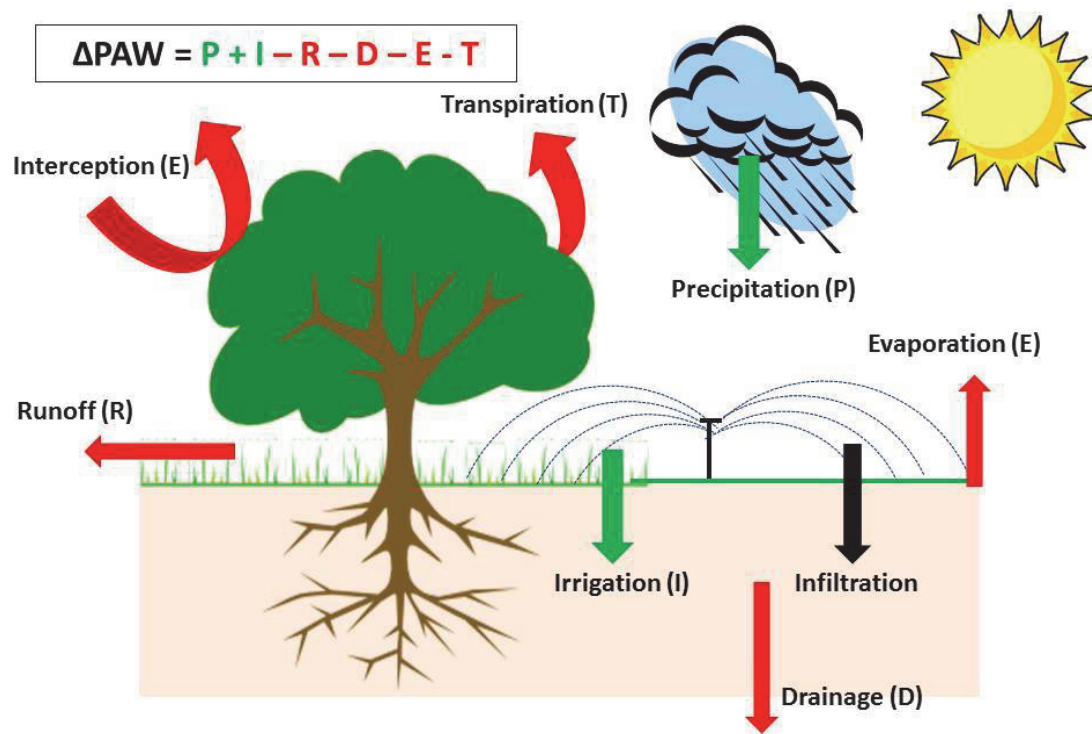


Figure 12. Components of the water balance equation in irrigated orchards.

Rana and Katerji (2000) comment that since it is often very difficult to accurately measure all the terms of Eq. (1), it is often expressed in its simplified form:

$$P + I - ET = \pm[\Delta S] \quad (2)$$

These simplifications make this method more applicable to catchment studies but unsuitable for precise ET measurements. Similarly, Gong *et al.* (2007) comment that the soil water balance method is, in principle, a simple method for estimating total evaporation, however, it requires accurate estimates of its components, such as deep drainage and change in soil water content. On the positive side Fares and Alva (2000) note that continuous monitoring of soil water content within and below the rooting zone can facilitate optimal irrigation scheduling aimed at minimizing both the effects of water stress on the plants, and also the leaching of water below the root zone, which can have adverse environmental effects.

1.8.2 Micrometeorological methods

Total evaporation (ET) from a vegetated surface such as an orchard may be determined directly or indirectly using micrometeorological methods which use the shortened energy balance approach (Thom, 1975).

$$R_n - G - LE - H = 0 \quad (3)$$

where (R_n) is the net (incoming minus reflected) irradiance above the canopy surface, (G) is the energy required to heat soil – referred to as soil heat flux, and (H) the energy required to heat the atmosphere – referred to as sensible heat flux. These are necessary because total evaporation (ET) is a function of the residual term LE – referred to as latent energy (the energy required to evaporate water), which closes the shortened energy balance equation. LE is the product of the specific latent heat of vaporisation, L (in J kg^{-1}) and the water vapour flux density E ($\text{kg s}^{-1} \text{m}^{-2}$). The equation may be re-arranged in the following way to solve for LE :

$$LE = R_n - G - H \quad (4)$$

Knowing the latent energy of vaporisation L to be equivalent to 2453 MJ kg^{-1} , evaporation (E) may consequently be derived from measurements of R_n , G and H .

Eddy Covariance

The Eddy Covariance (EC) technique (Savage *et al.*, 1997; Savage *et al.*, 2004) is often regarded as the standard, most direct method by which evaporation rates can be measured. It is a popular method for the estimation of total evaporation from a vegetative surface since it is a method that allows for the direct or indirect measurement of H and LE . Direct measurements are based on very high frequency (10 Hz) measurements of water vapour and CO_2 above vegetation canopies, e.g. using a LI-COR 7500 open path infrared gas analyzer (LI-COR, Lincoln, Nebraska, USA). Measurements determine gas concentrations in eddies of air that are particularly important drivers of gas exchange above aerodynamically rough vegetation. The system records changes in air movement, temperature, water vapour and CO_2 concentration every tenth of a second. Where vertical air movement and concentration of water vapour or CO_2 are correlated, there will be a net flux, and these are typically integrated over a period of 30 minutes. Alternatively, LE may be estimated indirectly as a residual from the shortened energy balance equation by measuring R_n , H and G . Sensible heat (H) may be estimated using a three-dimensional ultrasonic anemometer. This instrument provides measurements of the three components of wind velocity (u , v and w) as well as an estimate of

air temperature using sonic temperature (T_{sonic}) corrected for the influence of water vapour pressure on the speed of sound (Schotanus *et al.*, 1983). Sensible heat is estimated as

$$H_{EC} = \rho_a c_p \Sigma(w - \bar{w})(T_{sonic} - \bar{T}_{sonic}) \quad (5)$$

where ρ_a is the density of air (approximately 1.12 kg m^{-3}), c_p is the specific heat capacity of air at constant pressure (approximately $1040 \text{ J kg}^{-1} \text{ K}^{-1}$), w is the vertical wind velocity, T_{sonic} is the air temperature using sonic temperature, and the over bar denotes the average value during a time period of suitable length.

Scintillometry

A scintillometer is a device that optically measures the intensity fluctuations of visible or infrared radiation, caused by interference after the radiation has been scattered by inhomogenities of the refractive index of the air along the path of propagation. There are two types of scintillometers: small aperture scintillometers and large aperture scintillometers. Small aperture scintillometers operate at a range between 50 and 250 m, while large aperture scintillometers are able to operate at distances of between 500 m and 5 km. With small aperture scintillometers the observed intensity fluctuations are a measure of the structure parameter of the refractive index (C_n^2), and the inner scale of turbulence (l_o) of the air. The structure parameter of temperature (C_T^2) and kinetic energy dissipation rate (ε) can be obtained from C_n^2 and l_o . Application of the Monin-Obukhov similarity theory to C_T^2 and ε gives the turbulent fluxes of heat and momentum and the stability of the atmosphere. The sensible heat flux density is estimated as follows:

$$H = \rho C_p u_* T_* \quad (6)$$

where ρ is the density of air, C_p is the specific heat capacity of air at constant pressure, u_* is the friction velocity, and T_* is turbulent temperature scale. Additional measurements of radiation flux balance and soil heat flux are required to close the energy balance equation, allowing the latent heat flux (which provides the estimate of ET) to be calculated as a residuum of the other components.

Gong *et al.* (2007) note that there are difficulties in using some micrometeorological methods (typically the Eddy Covariance technique) because of canopy heterogeneity within orchards. However, scintillometry overcomes that problem to a large extent through spatial averaging (i.e. the scintillometer integrates ET measurements over the entire beam length, using a single instrument).

1.8.3 Soil evaporation and transpiration combination method

In terms of irrigation, the importance of separating measurements of soil evaporation and transpiration is that crop transpiration is often used to estimate productivity while soil evaporation is often regarded as an unproductive use of water (Kite and Droogers, 2000). The heat pulse velocity (HPV) technique is an appropriate technique for the measurement of sap flow rates (transpiration) in trees, and may be combined with the use of micro-lysimeters in the soil to derive the different components of total evaporation.

Heat Pulse Velocity Technique (Heat Ratio Method)

The heat ratio method (HRM) applied in the Heat Pulse Velocity (HPV) technique, as described in Burgess *et al.* (2001) is better suited to measuring low and reverse rates of sap flow than the Compensation Heat Pulse method (CHPM).

The HRM measures the ratio of the increase in temperature, following the release of a pulse of heat, at points equidistant below and above a heater probe. In order to achieve this, three parallel holes are accurately drilled (with the help of a drill guide strapped to the tree) into the sapwood (xylem) portion of tree trunks. The upper and lower holes are both situated 5 mm from the central hole (above and below, respectively). Copper-constantan thermocouples, wired to a multiplexer or logger, are inserted into the upper and lower holes to a specific depth below the cambium (below-bark insertion depth). A heater probe, wired to a relay control module, is inserted into the central hole.

At a pre-determined time interval (usually hourly), the temperatures in the upper and lower thermocouples are measured and the ratio (upper over lower) is logged. Directly thereafter, the central (heater) probe releases a short (0.5 second) pulse of heat, which diffuses through the adjacent wood and is taken up by the sap moving upwards through the xylem of the tree. As

the heat pulse is carried up the tree by the sap, the upper thermocouple begins to warm. Logging of the changing heat ratio commences 60 seconds after the initiation of the heat pulse and is measured continuously (approximately every second, depending on the processing speed of the logger) until 100 seconds after the heat pulse. Heat pulse velocity is calculated as (Burgess *et al.*, 2001):

$$V_h = \frac{k}{x} \ln \left(\frac{V_1}{V_2} \right) 3600 \quad (7)$$

where k is the thermal diffusivity of green (fresh) wood, x is a distance (cm) between heater and either temperature probe, and v_1 and v_2 are increases in temperature of initial temperatures) at equidistant points downstream and upstream, respectively, x cm from the heater. The probe distances relative to the heater probe are typically -0.5 and 0.5 cm, hence $x = 0.5$ cm. Ratios of V_1/V_2 approach an ideal value asymptotically, with the rate of change decaying exponentially. However after 60s the rate of change becomes very small and essentially linear.

The heat pulse velocity is corrected for wound size or width according to Swanson and Whitfield (1981) who developed a finite-difference numerical model to produce a simple equation for wound correction which was modified by Burgess *et al.* (2001) for the HRM:

$$V_c = b V_h + c V_h^2 + d V_h^3 \quad (8)$$

where b , c and d are correction coefficients derived for the wound size, diameter of Teflon probes (thermocouple probes) and probe separation distance.

Finally, the sap flux density (V_s) is calculated from the corrected heat pulse velocity (V_c) (Marshall, 1958):

$$V_s = \frac{V_c \rho_b (C_w + m_c C_s)}{\rho_s C_s} \quad (9)$$

where ρ_b is the dry wood density (kg m^{-3}), ρ_s the density of water, m_c the fractional water content of the sapwood on a dry weight basis (unit less), and c_w and c_s specific heat capacity of the wood matrix ($1200 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$) and sap water ($4182 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$) respectively.

Further measurements of sapwood area, water content and density, as well as the width of wounded (non-functional) xylem around the thermocouples, are used to convert sap velocity to a total sap flow rate for the entire sample tree. These measurements are usually taken at the termination of the experiment due to the destructive sampling required to obtain them. The conversion of sap flux density to sap flow is readily derived as the product of sap flux density and cross-sectional area of conducting sapwood. Gross wood cross-sectional area is calculated from its under-bark radius. Heartwood is discounted by staining the sapwood or by observing the dark colour often associated with heartwood. Where sap flux density is estimated at several radial depths, total sapwood area is divided into concentric annuli delimited by midpoints between measurement depths. In this way, point estimates of sap flux density are weighted according to the amount of conducting sapwood in the annulus they sample.

The number of probe sets (2 thermocouples and one heater) utilised per tree is determined by the diameter of the tree, but range from 4 to 12. The thermocouples are inserted to four different depths, since flow rates are typically fastest in the younger xylem near the cambium and slower in the older, deeper xylem (Figure 13). Data loggers are programmed to initiate the heat pulses and record the heat ratio changes in the two thermocouple sensors.

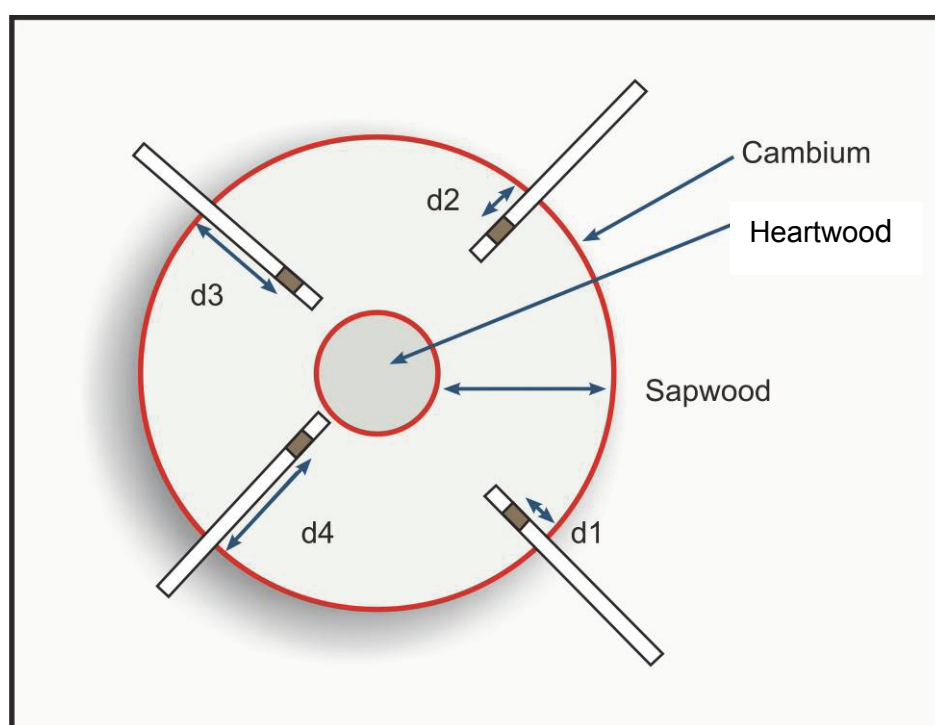


Figure 13. Illustration of different probe set insertion depths applied in the Heat Pulse Velocity technique.

Gong *et al.* (2007) conclude that the combination of soil evaporation and plant transpiration measurements is likely to be more accurate than the soil water balance and micrometeorological methods. This sentiment is shared by Trambouze *et al.* (1998) who suggest that the combined use of these two techniques enables both the actual total evaporation of the field and the relative importance of the evaporation and transpiration fluxes to be estimated. This approach gets round the environmental difficulties already mentioned of using the traditional methods. It obviates the need to determine the soil zone affected by root water uptake and can be applied in varying soil and slope conditions. As it is based on local measurements, however, it is subject to sampling constraints to assess the mean behaviour of the field (Trambouze *et al.*, 1998). In a no-rainfall period, the mean daily total evaporation of trees in an orchard may be calculated as:

$$ET = T + E_s \quad (10)$$

where ET (mm.day⁻¹) denotes the total evaporation of the trees using heat pulse and micro-lysimeter, T (mm.day⁻¹) denotes the weighted mean transpiration of the trees, and E_s (mm.day⁻¹) denotes the mean soil evaporation as measured with micro-lysimeters (Gong *et al.*, 2007).

1.9 Water use information

The various techniques for measuring the water use of fruit tree orchards have been briefly reviewed above. These may be grouped into those that measure transpiration within individual trees (single-tree techniques, e.g. the heat pulse velocity technique), and those that measure total evaporation from the orchard as a whole, either using an energy balance approach (e.g. eddy covariance or scintillometry) or a soil water balance approach (e.g. lysimetry or soil water measurements). An international literature search revealed that sap flow studies of fruit trees and orchard crops, using the heat pulse velocity technique, have been conducted on apple trees (Green and Clothier, 1988; Li *et al.*, 2002; Green *et al.*, 2003a; Green *et al.*, 2003b; Dragoni *et al.*, 2005; Gong *et al.*, 2007), pear trees (Caspari *et al.*, 1993; Kang *et al.*, 2002; Kang *et al.*, 2003; Ma *et al.*, 2007), peach trees (Gonzales-Altozano *et al.*, 2008), apricot trees (Nicolas *et al.*, 2004; Alarcón *et al.*, 2000), citrus trees (Rana *et al.*, 2005; Alarcón *et al.*, 2006) and cashew nut trees (Oguntunde *et al.*, 2004). In addition to the above, water use studies using other methods (e.g. soil water balance, Eddy Covariance and lysimetry techniques) have been conducted on citrus orchards (Fares and Alva, 1999; Green and Moreshet, 1979; Rogers *et al.*, 1983; Castel, 1997; Yang *et al.*, 2003), peach trees

(Mitchell *et al.*, 1991; Ayars *et al.*, 2003), bananas (Robinson and Alberts, 1989) and plum trees (Chootummatat *et al.*, 1990). A single reference to the use of scintillometry over fruit trees was found (Kite and Droogers, 2000) however, these measurements were done over a mosaic of different crops comprising 60% raisin grape, 15% cotton, 15% fruit trees, 5% other trees and 5% pasture. A summary of these results is presented (Table 20).

Table 20. A summary of measured water-use rates across a range of fruit tree species, from published literature.

Crop	spha	Age	Location	MAP	Measurement Period	Technique	Component measured	Ave Water Use	Max Water Use	Reference
Apple	1040	8yrs	China	630 mm	Apr-Oct (dry)	Sap flow and micro-lysimeter	ET	2.3 mm.day ⁻¹ (22 l.day ⁻¹)	6.5 mm.day ⁻¹ (63 l.day ⁻¹)	Gong <i>et al.</i> , 2007
Apple		10yrs	New Zealand	?	15days (summer)	Sap flow	T	27 l.day ⁻¹	37 l.day ⁻¹	Green <i>et al.</i> , 1989
Dwarf Apple	1280	?	NY, USA	?	10 weeks	Sap flow and Gas exchange	T	2.6 mm.day ⁻¹ (20 l.day ⁻¹)	5.1 mm.day ⁻¹ (40 l.day ⁻¹)	Dragoni <i>et al.</i> , 2005
Apple	?	14yrs	New Zealand	?	Summer to autumn	Sap flow and TDR soil water	T, and soil evaporation	(45 l.day ⁻¹)	3 mm.day ⁻¹ (70 l.day ⁻¹)	Green <i>et al.</i> , 2003b
Apple	1250	10yrs	Israel	?	May to Oct	Sap flow	T	4.4 mm.day ⁻¹ (35 l.day ⁻¹)	5.3 mm.day ⁻¹ (42 l.day ⁻¹)	Li <i>et al.</i> , 2002
Apple	1632	11yrs	Israel	?	May to Oct	Sap flow	T	3.1 mm.day ⁻¹ (19 l.day ⁻¹)	3.9 mm.day ⁻¹ (24 l.day ⁻¹)	Li <i>et al.</i> , 2002
Apple	1111	15yrs	Israel	?	May to Oct	Sap flow	T	4.3 mm.day ⁻¹ (39 l.day ⁻¹)	5.5 mm.day ⁻¹ (49 l.day ⁻¹)	Li <i>et al.</i> , 2002
Apricot	156	11yrs	Spain	?	July to Dec	Sap flow	T	1.1 mm.day ⁻¹ (70 l.day ⁻¹)	1.6 mm.day ⁻¹ (100 l.day ⁻¹)	Nicolas <i>et al.</i> , 2005
Apricot	?	3 yrs	Greenhouse (Spain)	?	2 Nov to 14 Nov	Sap flow, lysimeter	T	5-7 l.day ⁻¹	0.6 l.h ⁻¹	Alarcón <i>et al.</i> , 2000
Pear	1666	6yrs	Greenhouse (China)	632 mm	Apr to Oct	Sap Flow	T	0.8 mm.day ⁻¹ (6 l.day ⁻¹)	1 mm.day ⁻¹ (4.5 l.day ⁻¹)	Ma <i>et al.</i> , 2007
Peach	1132	3-6 yrs	Calif., USA	?	1991-1994	Lysimeter	ET	2.8 mm.day ⁻¹ (25 l.day ⁻¹)	9.5 mm.day ⁻¹ (84 l.day ⁻¹)	Ayars <i>et al.</i> , 2003

Crop	spha	Age	Location	MAP	Measurement Period	Technique	Component measured	Ave Water Use	Max Water Use	Reference
Peach	2500	5yrs	N Spain	? (drip irrig. 16 L h ⁻¹ tree ⁻¹),	DOY 190-204 (1997)	Sap flow (CHPM, stem heat balance, heat dissipation)	T, ET _o , soil evaporation, xylem pressure potential	3.8 mm.day ⁻¹ (15 l.day ⁻¹)	7 mm.day ⁻¹ (28 l.day ⁻¹)	Gonzales-Altozano <i>et al.</i> , 2008
Citrus	?	15 yrs	RSA, Sundays River Valley	?	2 years	Lysimeter	ET	?	6.1 mm day ⁻¹	Green and Moreshet (1979)
Citrus	?	?	Florida, USA	?	8 years	Water balance	ET	3.3 mm day ⁻¹	5.0 mm day ⁻¹	Rogers <i>et al.</i> , 1983
Citrus (Clementine)	432	7-11yrs	Spain	?	5 years	Lysimeter	ET, soil evaporation	≈ 1 mm day ⁻¹	≈ 2.3 mm day ⁻¹	Castel 1997
Citrus (Clementine)	400	10yrs	Southern Italy	550 mm	29 Jul to 5 Sep	Sap Flow	T	4 mm.day ⁻¹ (100 l.day ⁻¹)	8 mm.day ⁻¹ (200 l.day ⁻¹)	Rana <i>et al.</i> , 2005
Citrus ('Murcott' oranges)	4444	8 yrs	Greenhouse (Japan)	?	1 Aug to 20 Sept	Lysimeter	ET	4.4 mm day ⁻¹	7.0 mm day ⁻¹	Yang <i>et al.</i> , 2003
					12 Jan to 20 March	Lysimeter	ET	0.4 mm day ⁻¹	1.4 mm day ⁻¹	
Citrus (Navel orange)	337	4 yrs	Calif., USA	?	July to Aug	Energy balance (surface renewal)	ET	?	0.7 mm h ⁻¹ (20.8 l h ⁻¹)	Consoli <i>et al.</i> , 2006a,b
	299	15 yrs						?	0.8 mm h ⁻¹ (26.8 l h ⁻¹)	
	284	34-36 yrs						?	0.9 mm h ⁻¹ (31.7 l h ⁻¹)	

Crop	spha	Age	Location	MAP	Measurement Period	Technique	Component measured	Ave Water Use	Max Water Use	Reference
Citrus (Lemon) (1.5 m high, 2.5 cm stem diam, 1.2 m ² LA)	?	2yrs	Murcia, Spain	? (drip irrig. 4 L h ⁻¹ tree ⁻¹)	DOY 241-260 (2001)	Sap Flow (CHPM)	T, trunk diameter fluctuations, PS (CO ₂), WUE, leaf water potential	(1.4 l.day ⁻¹)	(1.8 l.day ⁻¹)	Alarcón <i>et al.</i> , 2006
Cashew Nut	?	?	?	?	22 days (wet to dry)	Sap Flow	T	0.7 mm.day ⁻¹	0.7 mm.day ⁻¹	Oguntunde <i>et al.</i> , 2004
Cashew Nut	?	?	?	?	22 days (wet to dry)	Eddy Correlation	ET	2.7 mm.day ⁻¹	3.2 mm.day ⁻¹	Oguntunde <i>et al.</i> , 2004

1.9.1 Water use of deciduous fruit tree species

Due to the importance of deciduous fruit on world markets, there have been numerous attempts over the years to quantify water use of these fruit trees. Many of these attempts would have involved the calculation of soil water balances, but as this approach has shown to be problematic, a few of the more recent reports on water use of deciduous fruit trees will be discussed below.

Water use of a drip-irrigated, mature, late-season peach cultivar 'O'Henry' was determined in four consecutive years on large weighing lysimeters in California (Ayars *et al.*, 2003). Water use of the peach tree orchard over the four years is presented (Table 21). Average yearly water use, over this 4 year period, was 1034 mm.

Table 21. Monthly water use of mature 'O'Henry' peaches measured with a weighing lysimeter (L) and calculated (C) using a three-segment linear model based on the lysimeter data (Ayars *et al.*, 2003).

Month	Water use (mm)							
	1991		1992		1993		1994	
	L	C	L	C	L	C	L	C
March	22	20	26	27	24	23	25	29
April	48	69	66	75	69	61	58	62
May	104	122	147	133	139	110	107	113
June	144	166	173	174	207	169	186	187
July	194	215	202	210	249	220	229	213
August	169	187	198	199	229	196	195	179
September	139	136	148	142	151	150	128	131
October	104	95	93	88	93	95	69	78
Total	927	1010	1053	1048	1161	1024	997	992

Peak water use of the peach trees occurred in July and August, which was approximately a month after maximum reference ET_o (Ayars *et al.*, 2003). When assessing a practical approach to scale AWS-generated ET_o to crop water use, mid-day canopy light interception was found to correlate well with K_c and was able to account for most of the observed variability in K_c over the course of the experiment (Ayars *et al.*, 2003). However, it could not account for a temporary post-harvest decline in water use at the end of August. A crop co-factor curve was fitted to the ET_o curve and it was found that a three-segmented linear or cubic regression fitted the data best. The maximum K_c factor determined using these regression curves was 1.06.

Alarcón *et al.* (2000) evaluated sap flow as an indicator of both transpiration and tree water status in 3 year-old 'Bulida' apricot trees grown in pots for a 12 week period during early summer. Transpiration of the trees was measured using a lysimeter approach, as the pots were placed on top of a weighing balance, which in turn was connected to a logger. Maximum sap flow rates were typically observed a few hours after midday and reached a maximum of 0.6 L h^{-1} , which equated to a daily water use of between 5 and 7 L. These authors also examined sap flow and transpiration under water stress conditions and following re-irrigation and it was found that under water stress conditions sap flow underestimated actual transpiration, but following re-irrigation, sap flow overestimated transpiration, which corresponded to an increase in leaf turgor potential (Alarcón *et al.*, 2000). Sap flow is therefore not an accurate estimate of transpiration during rapid dehydration and rehydration of plant tissues. A lack of correlation between heat-pulse and lysimeter determinations of plant water use in water-stressed plants was also observed in Asian pear trees by Caspari *et al.* (1993).

Gong *et al.* (2007) conducted field experiments to investigate the effects of leaf area index and soil water content on total evaporation and its components within an apple orchard in northwest China for 2 years. Total evaporation in the non-rainfall period was estimated using two approaches: the soil water balance method based on tube-type time-domain reflection measurements, and sap flow plus micro-lysimeter methods. The two methods were in good agreement, with differences usually less than 10%. The components of total evaporation varied with canopy development. During spring and autumn, soil evaporation was dominant as a result of low leaf area index. In summer, plant transpiration became significant, with an average transpiration to total evaporation ratio of 0.87. In contrast, Oguntunde *et al.* (2004) found that tree transpiration accounted for only about 25% of the total evaporation from a young cashew orchard.

The importance of canopy size in determining tree water use was demonstrated by Goodwin *et al.* (2006), who were able to demonstrate a drastic decline in water use of an isolated peach tree following debranching over a 15 day period. Debranching did not affect the time at which the daily maximum value for water use occurred, but had a remarkable impact on water use, with maximum water use declining from 3.8 l h^{-1} to 1.99 l h^{-1} , as leaf area declined from 51.99 m^2 to 7.7 m^2 . Daily water use therefore declined from 39.5 l day^{-1} to 11 l day^{-1} . These authors used this data to find a relatively simple measurement of canopy characteristics to adjust crop coefficients for different climatic and managerial combinations. They found that effective area of shade (the area of shade on the soil surface during the major part of the

day) was a good parameter to adjust K_c values (Goodwin *et al.*, 2006). The authors do, however, caution when scaling these results up from a single tree to a hedgerow orchard.

Dragoni *et al.* (2005) also concluded that there was a good correlation between measured transpiration rate and leaf area of apple trees. They found it useful to express transpiration rates in apple trees as a function of leaf area. They estimated daily rates of transpiration, normalized by canopy leaf area, to average $1.5\text{--}2 \text{ l.day}^{-1}.\text{LA}^{-1}$ (where LA is m^2 of leaf area) in June and July, with peaks around $2.0\text{--}2.5 \text{ l.day}^{-1}.\text{LA}^{-1}$. They found the leaf area of the dwarf apple trees to be approximately 14 m^2 corresponding to a full orchard leaf area index (LAI) of 1.8. Green *et al.* (2003b) measured mid-summer transpiration rates of about $60\text{--}70 \text{ l.day}^{-1}$ in 14-year-old 'Splendour' apple trees with a leaf area of about 45 m^2 (i.e. $1 \text{ to } 2 \text{ l.day}^{-1}.\text{LA}^{-1}.\text{tree}^{-1}$). Green *et al.* (1989) also observed significant night-time sap flow rates in apple trees. They found that nocturnal transpiration increased linearly with mean saturation deficit (vapour pressure deficit), which in turn increased with mean wind speed, so that nocturnal transpiration was greater on windy nights.

Pereira *et al.* (2007) successfully estimated the daily sap flow of irrigated, non-stressed apple trees in an orchard using inputs of tree leaf area (LA, in $\text{m}^2.\text{tree}^{-1}$), net (all-wave) radiation over grass (RN, in $\text{MJ.m}^{-2}.\text{day}^{-1}$) and the average air temperature. Tree leaf area ranged between 8.65 m^2 for a dwarf apple and 35.5 m^2 for a large apple. Daily sap flow (S, $\text{MJ.tree}^{-1}.\text{day}^{-1}$) was empirically found to equal approximately $1/4$ of RN times LA. However, they acknowledged that the problem then shifts to that of obtaining a reliable estimate of tree leaf area either by destructive sampling or other methods. Li *et al.* (2002) also found that a central problem in estimating orchard transpiration was the determination of canopy structure, namely the quantity of leaf area (LA, usually expressed at LAI), and the distribution of radiation on that LA. They stated that tools for the accurate estimation of canopy size and structure were lacking in irrigation studies, but contended that canopy structure could be measured using the gap fraction inversion method. They showed that Leaf Area Index in apple trees could be estimated using this method. Rana *et al.* (2005) applied the relationship between branch diameter and leaf area to estimate whole tree leaf area.

Various calibration methods for sap flow measurements have been conducted, specifically on apple trees. Green and Clothier (1988) found good correlations between sap flow (measured using the Compensation Heat Pulse Method) and the cut stem technique, in apple trees. They concluded that the sap flow technique was particularly suited to apple trees because of the small, short, closely spaced and interconnected nature of the xylem vessels in this

species, which upheld the assumption of thermal homogeneity required for this method. Dragoni *et al.* (2005) calibrated measurements of sap flow using the heat pulse technique against simultaneous measurements of whole-canopy transpiration using gas exchange chambers. They observed a linear relationship between the two, but concluded that it may be necessary to calibrate sap flow measurements to obtain reliable estimates of transpiration from apple trees.

1.9.2 Water use of subtropical fruit tree species

As opposed to deciduous fruit trees, subtropical fruit trees are evergreen and are therefore capable of using water throughout the year. Attempts to estimate water use of these fruit trees have employed a wide range of techniques, but an accurate model for determining water use of these trees across a wide range of climatic and management combinations has yet to be determined. Information gathered in the estimation of water use in citrus, one of the world's most important subtropical crops, is presented in this section.

The determination of water use of mature citrus orchards through water balance calculations was performed by two research groups in the 1980's (Rogers *et al.*, 1983, Castel *et al.*, 1987). ET_c rates of immature and mature orchards were estimated to be between 4.1 and 5 mm during the irrigation season under humid conditions in Florida (Table 22) and between 2.1 and 4 mm from May to September in Valencia, Spain (Castel *et al.*, 1987).

Table 22. Evaporation and crop coefficient data for a developing citrus orchard with a grass cover in Florida (adapted from Rogers et al., 1983 and Consoli et al., 2006).

Month	ET _o (mm day ⁻¹)	ET _c (mm day ⁻¹)	K _{co}	K _{cf}	Rainfall (mm month ⁻¹)
January	2.2	1.9	0.86	0.95	59
February	2.9	2.2	0.76	0.95	50
March	3.7	2.7	0.73	0.95	43
April	4.8	3.1	0.65	0.90	52
May	4.5	4.2	0.93	0.90	176
June	4.5	5.0	1.11	0.90	183
July	4.3	4.5	1.05	0.90	168
August	4.1	4.2	1.02	0.90	124
September	3.7	4.1	1.11	0.90	216
October	3.2	3.3	1.03	0.90	95
November	2.4	2.4	1.00	0.90	69
December	1.9	2.0	1.05	0.90	70

ET_o is FAO 24 Penman-Monteith reference ET (Doorenbos and Pruitt 1975), ET_c is crop total evaporation, K_{co} is crop coefficient determined from ET_o and K_{cf} is from FAO 24 for citrus orchards in Florida grown with a cover crop.

Water balance approaches to fruit tree water use have been shown to be problematic and thus many researchers have used a more direct approach to ET_c determinations by using weighing lysimeters. In the late 1970's Green and Moreshet (1979) used weighing lysimeters in 15 year-old 'Valencia' orange orchards to estimate seasonal variation in water use characteristics over two seasons in the Sundays River Valley in South Africa. Highest monthly ET was found during January (approximately 190 mm month⁻¹) and lowest monthly ET during July (approximately 50 mm month⁻¹). This seasonal variation reflected energy input in terms of incident solar radiation in the orchard. These authors also found that daily variation in ET_o, as calculated from a Class A pan, was twice that of daily water use by the trees, possibly indicating that citrus tree conductance responds to changing atmospheric demand in a compensatory manner (Green and Moreshet 1979). Castel (1997) also determined total evaporation of drip-irrigated Clementine citrus in Valencia, Spain using infield weighing lysimeters. Over a 5-year measurement period ET_c varied from approximately 0.5 mm day⁻¹ in winter to 2.25 mm day⁻¹ in summer. Annual K_c values increased as the trees grew and showed a significant linear correlation with ground cover, with maximum values occurring in autumn and minimum values in spring. Canopy resistance measurements displayed an opposite trend to K_c values, with lowest resistances in autumn and highest values in spring (Castel 1997).

Seasonal variation in citrus tree conductance (ratio of tree water use to ET_0) was largely attributed to three factors, viz. 1) the phenology of citrus trees (spring and autumn flushes and pruning), 2) day-to-day responses to seasonal atmospheric demand fluctuations and 3) variations in wind occurrence, which affects atmospheric resistance (Green and Moreshet 1979, Castel 1997). Green and Moreshet (1979) argued that a physiologically-based conductance measurement should be more or less constant across production areas and could be used to derive crop coefficients for specific areas.

More recently, Yang *et al.* (2003) estimated total evaporation from 8 year-old 'Murcott' orange trees (canopy volume 0.38-0.4 m³) in a greenhouse using lysimeters, with the view of assessing variations in hourly and daily total evaporation rates. These authors performed measurements in summer (50 days) and winter (65 days) and found that average ET varied from 0.4 mm day⁻¹ during winter to 4.4 mm day⁻¹ in summer. Monthly K_c factors also showed a distinct seasonal variation with an average K_c (summer) of 0.91 and an average K_c (winter) of 0.75. Daily variations in ET were also found during summer and winter monitoring periods, with greater variation observed during the summer months than winter months. This variation was attributed to microclimate conditions in the greenhouse (Yang *et al.*, 2003). Using sap flow studies, Alarcón *et al.* (2006) showed that covering young (2yr old) citrus (Lemon) orchards with aluminised-plastic shade netting increased their water-use efficiency (WUE), compared to un-shaded control trees. They showed that, relative to the control trees, sap flow rates of shaded trees were reduced by the netting, while net photosynthetic rates (CO₂ assimilation) were slightly improved, thereby increasing their WUE.

Consoli *et al.* (2006a,b) estimated total evaporation and light interception by 'Frost Nucellar' Navel orange canopies of varying ages during July and August in California. These authors estimated hourly ET_c through micro-meteorological measurements and the surface renewal method. ET was determined as a residual of the energy balance and was assumed to be equal to ET_c , since orchards were well-managed and there was little transpiration-reducing water stress (Consoli *et al.*, 2006a). During a month in summer ET_c rates peaked between 0.8 and 0.9 mm h⁻¹ in mature orchards (34-36 year-old trees, ground cover = 70%), between 0.7 and 0.8 mm h⁻¹ for 15 year-old orchards (ground cover = 47%) and between 0.6 and 0.7 mm h⁻¹ in 4 year-old trees (ground cover = 20%). Average hourly K_c of 0.94 for mature orchards and 0.58 to 0.75 for immature orchards (4 and 15 year-old trees respectively) were subsequently determined (Consoli *et al.*, 2006), which were higher than those published in FAO 24 (Doorenbos and Pruitt 1975) and FAO 56 (Allen

et al., 1998) reports. Through the evaluation of different sized trees these Consoli *et al.* (2006a,b) were able to demonstrate that water use was closely related to PAR intercepted by the canopies (up to 0.65%), percentage ground cover (up to 60%) and LAI (up to 3 m² m⁻²).

Snyder and O'Connell (2006) evaluated total evaporation over a 4-year period in the 34-36 year orchard, used for the experiments by Consoli *et al.* (2006a,b), in order to determine crop coefficients for microsprinkler-irrigated, clean-cultivated citrus in an arid environment. Average ET_o and K_{co} values obtained over the 4-year period are shown (Table 23).

Table 23. Average mean daily reference total evaporation (ET_o), observed crop coefficients (K_{co}) and crop total evaporation (ET_c) for fully mature, clean-cultivated, microsprinkler-irrigated navel orchard in California for 2003 and 2004 (Snyder and O'Connell, 2006).

Month	ET _o (mm day ⁻¹)	K _{co}	ET _c (mm day ⁻¹)	K' _{co}	ET' _c (mm day ⁻¹)
January	0.9	1.90	1.7	1.15	1.0
February	1.5	1.61	2.4	1.15	1.7
March	3.0	1.37	4.1	1.15	3.5
April	3.9	1.22	4.8	1.15	4.5
May	5.5	1.10	6.1	1.10	6.1
June	6.5	1.03	6.7	1.00	6.5
July	6.6	0.96	6.3	1.00	6.6
August	5.7	1.02	5.8	1.00	5.7
September	4.6	1.02	4.7	1.00	4.6
October	3.2	1.07	3.4	1.05	3.4
November	1.3	1.70	2.2	1.15	1.5
December	0.9	1.79	1.6	1.15	1.0

K'_{co} – recommended mature crop coefficient, ET'_c – daily crop total evaporation calculated using K'_{co} and ET_o

The much higher K_c values reported by Snyder and O'Connell (2006) from June till August, as compared to the values reported in the FAO reports by Doorenbos and Pruitt (1975) and Allen *et al.* (1998), were attributed to different irrigation systems. Snyder and O'Connell (2006) reported on crop coefficients for microsprinkler-irrigated citrus, whilst those included on the FAO reports were probably derived from furrow or flood-irrigated citrus orchards. This indicates the dependency of crop coefficients on production practices and local climatic conditions and the need for a more robust indication of plant water use for irrigation scheduling purposes. It should be noted that crop coefficients presented in Table 23 are only recommended by

the authors for microsprinkler-irrigated citrus grown under similar conditions to the experimental orchard.

The variation in reported water use rates of citrus reflects the wide range of cultivars and rootstocks available, climatic conditions under which the trees are grown, tree size and irrigation methods. Cognisance of these parameters needs to be taken into account when determining more robust crop coefficients for different production systems and in fact the question needs to be asked if the crop coefficient model is applicable to citrus water use.

1.10 Appropriate models

In order to verify and extrapolate measured water use rates of fruit tree species to wider regions in South Africa, suitable models need to be identified and tested. Once the measured sap velocity data have been converted into actual sap flow (transpiration) rates, the data set will be ideal for testing the suitability of various models to accurately simulate transpiration in these species. However, before effort is expended in setting up any particular model it is important to first gauge the appropriateness of using that model. Numerous aspects need to be considered including the availability of required input data, ability of the model to simulate the desired processes, complexity of operation (ease of use / user support) etc. Four models are proposed for evaluation in this project, namely the SWB model, the MAESTRA model and the FAO-56 model. Brief descriptions of the three models appear below.

1.10.1 Soil Water Balance model (SWB)

A mechanistic, real-time, generic crop growth / soil water balance model, named the Soil Water Balance (SWB) model was developed by Annandale *et al.* (1999), as an irrigation management technology. From soil, weather and crop inputs it simulates crop growth and provides insights into the one-dimensional biophysical links between the atmosphere (environment), plant systems and the soil system. It has been calibrated and tested under a range of conditions and crops and has proven to be very helpful, with reliable correctness. Subsequent to the development of the original SWB model, a new version that performs energy interception and water balance modelling in two dimensions, by trees planted in hedgerows (SWB-2D), was developed and verified as an extension of the former model. The latter model has four components, namely: a tree canopy radiation interception simulator, a soil evaporation simulator, a tree transpiration simulator and a simulator of water redistribution in the soil. These components have been evaluated both

independently and together, and have shown that the model and its components are accurate. The two-dimensional model was incorporated into the original SWB model (Annandale *et al.*, 1999; Annandale *et al.*, 2002; Annandale *et al.*, 2003; Annandale *et al.*, 2004).

1.10.2 MAESTRA model

The MAESTRA model (Medlyn, 2004) is a development of the earlier MAESTRO model (Wang and Jarvis, 1990). It is an array model that predicts radiation absorption, photosynthesis and transpiration in individual tree crowns as well as in the stand as a whole. It has proved useful as a research tool for scaling up leaf measurements to the whole canopy and whole stand. Medlyn (2004) documents the wide range of applications that this model has found since it was developed in 1988. MAESTRA is briefly described as follows¹:

- The forest canopy is represented in the model as an array of tree crowns whose positions and dimensions are specified.
 - Positions in X, Y and Z co-ordinates.
 - Crown radius
 - Crown length
 - Height to crown base
- Calculations are performed for just one crown, the target crown
- The time scale is in hours, generally one hour
- The distribution of leaf area within the target crown is specified.
 - Crown shape
 - Leaf area distribution
- The main meteorological driving variables are incident radiation, temperature and humidity. Mean atmospheric CO₂ concentration is specified.
- The target crown is divided into grid points (up to 120) and the radiation penetrating to each point is calculated for three wavebands (PAR, near infrared and longwave). Direct, diffuse and scattered radiation are considered separately.
 - Hourly sun position in the sky for specified date and latitude
 - Slope of ground taken into account
 - Leaf inclination
 - Leaf age class distribution

¹ This description of the MAESTRA model was provided by Dr. Peter Dye.

- The absorbed PAR at each grid point drives the photosynthesis and transpiration routines
- Photosynthesis is calculated from the Farquhar-von Caemmerer model
 - Jmax
 - Vcmax
 - Leaf N content
- Stomatal conductance can be calculated from one of three models (Jarvis, Ball-Berry or Ball-Berry-Leuning).
- Transpiration is calculated by applying the Penman-Monteith equation at each grid point, and summing over all grid points.
- Respiration calculated for leaves and branches/stems
- Output hourly or daily
- Useful validation data are intercepted PAR and H₂O fluxes

1.10.3 FAO-56 model

The FAO-56 model (Allen *et al.*, 2004) provides a means of calculating reference and crop total evaporation from meteorological data and crop coefficients. The effect of climate on crop water requirements is given by the reference total evaporation (ET_o), and the effect of the crop by the crop coefficient K_c. Actual crop total evaporation (ET_c) is calculated by multiplying ET_o by K_c as follows:

$$ET_c = K_c * ET_o \quad (11)$$

The calculation of ET_o is based on the Penman-Monteith combination method, and represents the total evaporation of a hypothetical reference crop (short grass). The technique uses standard climatic data that can be easily measured or derived from commonly collected weather station data. Differences in the canopy and aerodynamic resistances of the crop being simulated, relative to the reference crop, are accounted for within the crop coefficient (K_c). K_c serves as an aggregation of the physical and physiological differences between crops. Two calculation methods to derive crop total evaporation (ET_c) from ET_o are possible. The first approach integrates the relationships between total evaporation of the crop and the reference surface into a single coefficient (K_c). The second approach splits K_c into two factors that separately describe the evaporation (K_e) and transpiration (K_{cb}) components.

The FAO-56 publication lists crop coefficients for numerous crops under “standard conditions.” The list includes several fruit and nut tree species. These could be modified to better represent crop development stages (and

associated dates) actually observed for the species eventually selected for monitoring in this project. Multiplication of the reference evaporation by the crop coefficient represents the upper envelope of crop transpiration where no limitations are placed on plant growth or total evaporation. The option to split the crop coefficient (K_c) into two factors that separately describe the evaporation (K_e) and transpiration (K_{cb}) components is particularly suited to this particular study because the field data that will be collected will yield values of transpiration (excluding soil evaporation), and are consequently directly comparable to the simulated values of K_{cb} . The predicted transpiration may also be adjusted to non-standard conditions using stress modifiers. Another major advantage of FAO-56 is that all the necessary meteorological data to successfully run the model will be collected at site and will be sufficient to use as input into the model.

Due to its physical and biological basis, the FAO-56 Penman-Monteith model (PM) is the most frequently used method to estimate orchard water use (Pereira *et al.*, 2006). In a total evaporation experiment on apple trees Gong *et al.* (2007) found that the crop coefficient K_c showed a strong linear dependence on leaf area index. Their study concluded that prediction of total evaporation in apple orchards could be made using the FAO-56 crop coefficient method, from commonly available meteorological data in the area.

1.10.4 Penman-Monteith model

In the 1940s and in earlier decades, evaporation was calculated using either the energy balance or the aerodynamic approach. However, in 1948, Penman combined these two approaches resulting in an equation for calculating evaporation from an open water body which was a weighted sum of the available energy ($R_n - G$) and the aerodynamic approaches, where evaporation was a function of the wind speed and the surface to air vapour pressure deficit $f(e_s - e_a)$. R_n is the net radiation absorbed by a surface, G is the soil heat flux, e_s is the saturated vapour pressure at the water surface temperature and e_a the actual vapour pressure of the air above the water surface. The Penman equation was only valid on open water bodies e.g. reservoirs such as dams or evaporation pans where evaporation occurred at a potential rate. In 1965, Monteith further modified Penman's equation to include a surface resistance term (r_c , in $s\ m^{-1}$) and this led to the widely used Penman-Monteith (PM) equation which is of the form:

$$E = \frac{\Delta(R_n - G) + \rho c_p g_b [e_s(T_a) - e_a]}{\lambda \left[\Delta + \gamma \left(1 + \frac{r_c}{r_b} \right) \right]} \quad (12)$$

where λ is the latent heat of vaporization of water (J kg^{-1}), Δ is the slope of the saturation vapour pressure against temperature curve ($\text{Pa } ^\circ\text{C}^{-1}$), ρ is the density of air (kg m^{-3}), c_p is the specific heat of air at constant pressure ($\text{J kg}^{-1} ^\circ\text{C}^{-1}$), $e_s(T_a) - e_a$ is the vapour pressure deficit (VPD) of the air (Pa), γ is the psychrometric constant ($\text{Pa } ^\circ\text{C}^{-1}$), r_b the aerodynamic and r_c the canopy resistance (s m^{-1}). For a well-watered reference crop (height ~ 0.12 m) that completely covers the ground, the ET (in mm d^{-1}) can be derived from standard meteorological data using the following simplified PM equation according to Allen et al (1998):

$$E = \frac{0.408\Delta(R_n - G) + \frac{900}{273 + T_a} u_2 (e_s(T_a) - e_a)}{\lambda[\Delta + \gamma(1 + 0.34u_2)]} \quad (13)$$

where u_2 is the wind speed at 2 m height, $e_s(T_a)$ is the saturation vapour pressure at air temperature (T_a) and e_a is the actual vapour pressure of the air. This equation is widely used for calculating the reference evapotranspiration (ET_o).

In recent years some researchers have directly applied the PM equation to derive the ET of entire fruit tree orchards e.g. Rana et al (2005) and Consoli and Papa (2012). A key assumption in these studies is that entire orchards behave like uniform surfaces (a “Big Leaf”). They effectively ignore the heterogeneity which characterises most orchards. However, a larger number of researchers apply the PM equation to estimate only the transpiration component of ET and examples for fruit orchards can be found in Pereira *et al.* (2006); Oguntunde *et al.* (2007); Cohen *et al.* (1997) and Villalobos *et al.* (2000) while the soil evaporation component is modelled separately, for example by using the Priestly-Taylor formula (Li *et al.* 2010). Modelling the canopy resistance for fruit orchards is not a straightforward task given the complex water relations of some perennial species such as citrus, which is characterised by rapid cyclic opening and closure of the stomata which are often unrelated to environmental factors (Dzikiti et al., 2007; Steppe et al., 2006).

Both Rana et al (2005) and Consoli and Papa (2012) used the following relationship to determine the resistance factors in the PM equation for entire citrus orchards:

$$\frac{r_c}{r_a} = a \frac{r^*}{r_a} + b \quad (14)$$

where a and b are empirical calibration constants that require experimental determination; r^* is given by Monteith (1965) as:

$$r^* = \frac{s + \gamma}{s\gamma} \cdot \frac{\rho c_p D}{(R_n - G)} \quad (15)$$

D is the vapour pressure deficit of the air. In these models, the aerodynamic resistance was determined by the equation:

$$r_a = \frac{\ln(z - d)/(h_c - d)}{ku^*} \quad (16)$$

where z is the reference point above the canopy, d is the zero plane displacement estimated as $0.67 \cdot h_c$, h_c is the mean canopy height, k is the von Karman constant and u^* is the friction velocity that can be measured by an eddy covariance system. In situations where the ET is directly measured using micrometeorological methods together with the available energy components and weather data, the calibration constants “a” and “b” in equation 7 can be obtained from a linear regression of r_c/r_a vs r^*/r_a as implemented by Rana et al (2005) and Consoli and Papa (2012).

1.11 Conclusions

Tree transpiration studies often require that rates of water use be extrapolated from individual trees to that of stands and plantations. Wullschleger *et al.* (1998) emphasise that the ultimate success of that extrapolation depends in part on whether data covering short time sequences can be applied to longer periods of time. They conclude that techniques for estimating whole-tree water use have provided valuable tools for conducting basic and applied research, and that future studies that emphasise the use of these techniques by both tree physiologists and forest hydrologists should be encouraged. Through improved understanding of all the water-related aspects of the fruit tree industry, as reviewed in this document, together with relatively long monitoring periods and extrapolation modelling, as envisioned for this project, it is anticipated that improvements to the efficiency of water use within this important South African industry will be possible.

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APPENDIX A: HEAT PULSE VELOCITY SAP-FLOW MONITORING SYSTEM²

Application of a Heat Pulse Velocity sap flow monitoring system (heat ratio method) for measuring transpiration rates in woody plant species

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Abstract

This technical note summarises the basic theory, equipment, installation, operation, maintenance and data analysis requirements of the Heat Ratio Method of the Heat Pulse Velocity Technique for measuring sap flow and resultant transpiration of woody plant species.

Keywords: sap flow, water use, heat pulse velocity, heat ratio method

Introduction

Heat dissipation techniques are recognised internationally as an accepted method for measuring sap flow rates in trees and woody plants (Marshall, 1958; Swanson, 1994; Smith and Allan, 1996; Granier et al., 1996; Čermák et al., 2004). A variety of systems employing heat balance methods (e.g. Sakuratani, 1981), continuously heated probes (e.g. Granier, 1985;

² When making reference to this section, please cite as follows:

Gush, M.B., Dye, P.J., Clulow, A.D., Taylor, N.J., Everson, C.S., Dziki, S. and Naiken, V. 2014. Application of a Heat Pulse Velocity sap flow monitoring system (heat ratio method) for measuring transpiration rates in woody plant species. In: Taylor, N.J. and Gush, M.B. (Eds). 2014. The water use of selected fruit tree orchards (Volume 1): Review of available knowledge. Water Research Commission, Pretoria, RSA, WRC Report 1770/1/14, Appendix A.

Nadezhdina et al., 1998) or heat pulses (e.g. Green, 1998) have been developed, of which the Heat Ratio Method (HRM) of the Heat Pulse Velocity (HPV) technique (Burgess et al., 2001) is one. These systems essentially use heat as a tracer of sap flow, and are useful for the calculation of volumes of water used by plants over a specified period (short or long-term). They are unique in that they are able to quantify the volumes of water physically passing through individual plants at a high temporal resolution (e.g. hourly), using heat dissipation theory. In this way diurnal and seasonal patterns of water-use can be observed and water-use totals can be measured. When combined with additional inputs, this information may in turn be used to quantify aspects such as water-use efficiency, irrigation efficiency and water footprints. In eco-hydrological studies, some systems (e.g. HRM) can measure volumes of water moving from the soil into the plant, or reverse flows (from the plant into the soil) thereby providing insights on the mechanisms by which plants interact with the environment.

However, these methods of quantifying sap flow are highly technical and data intensive, requiring careful installation, regular maintenance, meticulous data management, calibration (where possible) and knowledge of physiological aspects of the plants being monitored. Practical skills in power supply management, basic electronics, use and programming of data-loggers, knowledge of complementary sensors (e.g. to measure soil water or weather variables), and attention to detail are essential if the systems are to be successfully employed. There still remain a number of challenges, which has limited their large-scale commercialisation and application in industry, and resulted in their use primarily in specialised research environments. Sap flow monitoring methods, including the Granier / thermal dissipation probe (TDP), Compensation Heat Pulse Velocity (CHPV) and HRM heat pulse velocity techniques have been extensively applied for research purposes in South Africa (Dye and Olbrich, 1993; Dye *et al.*, 1996; Gush, 2008; Gush and Dye, 2009; Dzikiti *et al.*, 2013; Clulow et al., 2013). This technical note summarises the basic theory, equipment, installation, operation, maintenance and data analysis requirements of one particular HPV system, namely the Heat Ratio Method (HRM).

Basic theory

The HRM HPV technique is essentially a tracer method which measures the rate with which heat pulses applied to the conductive xylem portion of woody stems are transmitted vertically by the flow of sap through the stem. Thermocouples (TCs) positioned in the sapwood of the plant are used to detect the velocity and direction with which heated sap passes through the stem. Ratios of temperature increases measured by these thermocouples,

following the release of a pulse of heat by a centrally positioned line heater are used to calculate the velocity of the heat pulses. The theory behind using heat as a tracer of sap flow dates back to Huber (1932), and there have been numerous refinements and multiple applications of the technique since then. A theoretical framework developed by Marshall (1958) established that heat pulse velocity may be calculated as:

$$V_h = \frac{k}{x} \ln(v_1 / v_2) 3600 \quad (1)$$

where V_h is the heat pulse velocity (cm h^{-1}), k is thermal diffusivity of the wood ($\text{cm}^2 \text{s}^{-1}$) assigned a nominal value of $2.5 \times 10^{-3} \text{ cm}^2 \text{s}^{-1}$ (Marshall 1958), x is distance (cm) between the heater and either temperature probe, v_1 and v_2 are increases in temperature (from initial temperatures) at equidistant points above and below the heater probe, and the multiplier of 3600 accounts for the need to scale measurements from seconds to an hourly value. The derivation of heat pulse velocity from the natural log of the average heat ratio multiplied by the above constants is the basis for the HRM, and makes it suitable for the measurement of low and reverse rates of sap flow in woody plants (Burgess *et al.*, 2001).

Equipment requirements

The HRM requires a central line heater to be implanted into the sapwood portion of the stem, and these are typically 60 mm long and made from 1.8 mm outside-diameter stainless steel tubing enclosing a constantan filament. Thermocouple (TC) probes (consisting of type T copper-constantan thermocouples embedded in 2 mm outside-diameter PTFE tubing), are inserted to a specific depth below the bark in two additional holes drilled equidistantly 5 mm above and below the heater probe (Figure 1). The diameter of the holes for the heater and TC probes are similar in size to the thicknesses of the probes, being 1.8 mm for the heater and 2.0 mm for the TCs probes respectively, to ensure a good thermal contact with the sapwood.

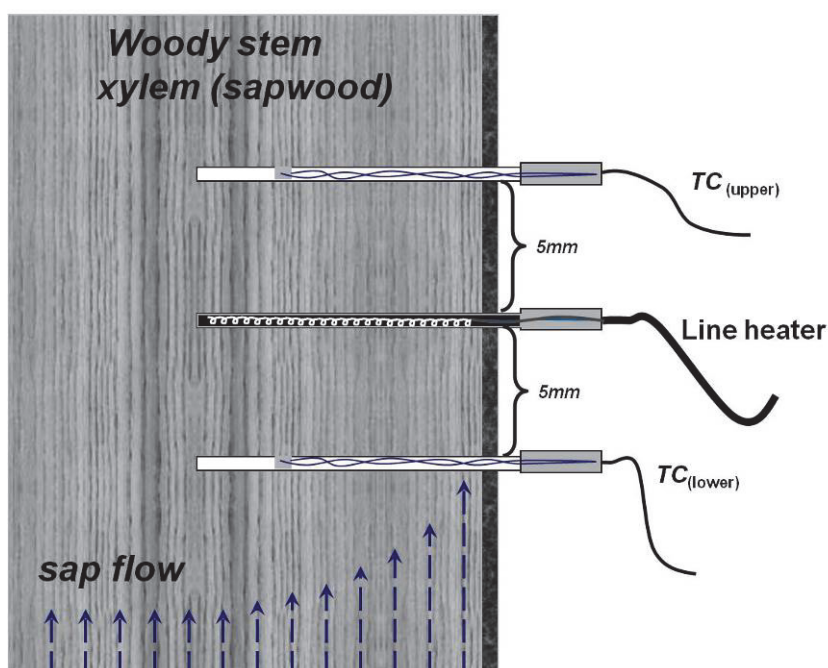


Figure 1. Longitudinal section through a woody stem, illustrating the positioning of the thermocouples and line heater of the HPV system (HRM method) to measure sap flow.

The thermocouples are typically wired to a 32-channel AM16/32A multiplexer and CR10X or CR1000 data-logger (Campbell Scientific, Logan, UT), which should be well earthed. The heater probes (typically consisting of four individual probes) form a heater cluster which is connected to a relay control module and 12 V battery. A solar panel or other means of auxiliary power may be used to continuously charge the batteries that power the system (at secure sites only due to the significant security risk in the use of solar panels). Generally, 4-12 sets of probes (each set comprising upper and lower TCs and a heater) are implanted at different depths into the sapwood of the stem, depending on the size of the tree. The data-loggers are programmed to initiate measurements at pre-determined intervals (generally hourly). Downloading of the data, as well as uploading revised programmes to the data-logger, can be done manually using Campbell Scientific software (Loggernet) in conjunction with a suitable cable physically connected between the data-logger and lap top, or remotely using a cellular phone modem connected to the data-logger. In order to minimise battery usage by the modem, it may be programmed to only switch on for a specific time each day during which time remote data transfer operations can be carried out. Good cell phone reception is mandatory for the remote download option to work. Security is important, and the systems are typically enclosed in robust strong-boxes to protect against theft and weather. Additional protection from disturbance by animals such as elephants, rhino, baboons and monkeys may be necessary at certain field sites, and this may be achieved by means of

pole, wire and shade-cloth structures angled against the trees, or electric fencing.

Installation

Sample trees should generally be healthy, undamaged, disease-free specimens with undisturbed crowns, representative of the larger orchard or forest stand, and without evidence of nutrient and / or water stress. When sampling a number of trees using a single sap flow monitoring system, the proximity of trees to each other is also a consideration due to limitations in the length of cabling associated with the HPV technique, and the necessity to wire all probes to a central location (multiplexer and / or data-logger). Maximum spacing between trees is typically 3-5 m (depending on probe cable length), beyond which additional hardware is required. Suitable locations for the insertion of the heat pulse velocity probes then need to be identified on the stems of the trees being sampled. It is important that the probes are inserted below the first branches having live foliage in order to capture all sap flow movement through the stem. It is also advisable to avoid inserting probes directly above or below knots in the wood, where branches (past or present) joined the stem, as these could disrupt or re-direct the flow of sap through the stem. The thermocouple (TC) probes are inserted to different depths below the cambium (Figure 2) to sample different regions of the sapwood, as sap flow velocities are known to vary radially across the xylem (Wullschlegel and King, 2000). The TC insertion depths may be determined by coring the tree stem using an increment borer (e.g. Haglöf, Sweden), and then arranging the measurement positions after identifying the sapwood depth visually or by staining (Kutscha and Sachs, 1962). Knowledge of the anatomical characteristics of the xylem, particularly whether the sapwood is non-porous (coniferous), diffuse-porous or ring-porous by nature, is also advantageous in deciding on probe insertion depths and/or interpreting the resultant sap flow data.

The need to determine the presence of the sapwood (xylem) / heartwood (non-conducting tissue) interface is important for determining probe insertion depths, but also for the calculation of final transpiration volumes, as described later. Although there is usually a limitation to the depth that TC probes can be inserted due to their design, for practical purposes sap velocities in the sapwood beyond the deepest probe depth may be assumed to equal velocities measured at the deepest probe. Drilling is usually performed with a battery-operated drill, using a drill guide strapped to the tree, to ensure that the holes are correctly aligned and spaced. Care needs to be taken that the holes are positioned parallel to the grain of the wood; a particular challenge in species where spiralling of stem wood may occur (e.g. *Lannea schweinfurthii*).

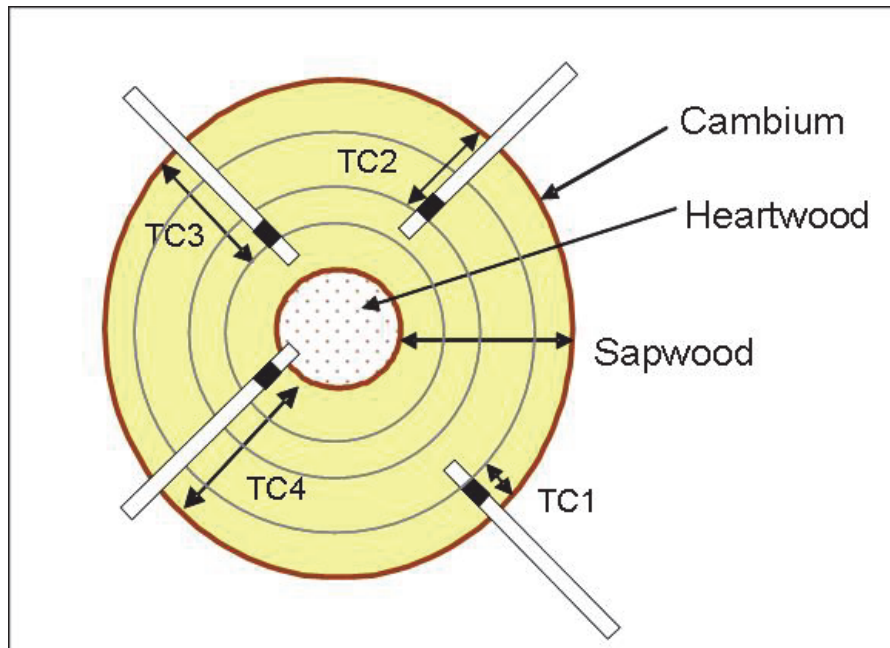


Figure 2. Stem cross-section illustrating a typical sampling pattern of thermocouples within the sapwood, and the associated sapwood areas represented by each thermocouple.

Corrosion, particularly of heater probes, may be a problem with certain tree species (e.g. *Acacia mearnsii* and *Spirostachys africana*), and coating the heater probes in a thin layer of petroleum jelly prior to insertion assists in alleviating this. Expulsion of the probes from the trees through exudation of resin is also common in some species (particularly *Acacia* spp.). Consequently, to reduce data loss it is recommended that all probes be checked and re-positioned regularly. To account for long-term changes in position as a result of stem diameter growth it is suggested that probes be completely removed from the tree and repositioned to their correct depths at least once a year (preferably in the spring before the production of new xylem and the flush of new leaves in deciduous species).

Operation of the HRM technique

A typical measurement cycle in the HRM technique progresses as follows: First the temperatures in the upper and lower TCs are measured 10 times and an average ambient pre-heating temperature is calculated for each TC prior to the injection of heat by the heater, and stored in the data-logger for later calculations. Immediately thereafter, a short pulse of heat (typically 0.4-0.6 seconds) is released through all the heater probes, via a relay control module, which regulates the current and sequentially turns on the individual heater clusters. The resultant pulse of heat diffuses through the adjacent wood and is taken up by the sap moving upwards through the xylem of the tree. As the

heat pulse is conducted up the tree by the sap, the upper thermocouples begin to warm (generally to a greater extent than the lower thermocouples due to heat transport by the sap during the day, although there is some conduction of heat to the lower thermocouple as well). Measurements of the post heating temperatures in all TCs are measured continuously (approximately every second) from 60 to 100 seconds after the heat pulse (after Burgess *et al.*, 2001). This is the period when the rate of change in v_1/v_2 becomes extremely small, ratios are effectively linear and v_1/v_2 may be determined by interpolating back to the time of the heat pulse (Figure 3).

Ratios of temperature increases measured by upper and lower thermocouples (TCs), following the heat pulse are subsequently used to calculate the heat pulse velocity. First the change in temperature (Δtemp) is determined for each TC. This equates to the post-pulse (heated) temperature minus the average pre-pulse (ambient) temperature determined earlier. The heat ratio (Δtemp upper TC / Δtemp lower TC) is measured continuously between 60 and 100 s after the heat pulse for each set of probes consecutively, and the average of these individual heat ratio values are calculated for each TC pair. The heat pulse velocity (for each TC pair) is then calculated according to Equation 1. The resultant heat pulse velocities for each TC set are the final outputs from the logger, but require further analysis, as explained later.

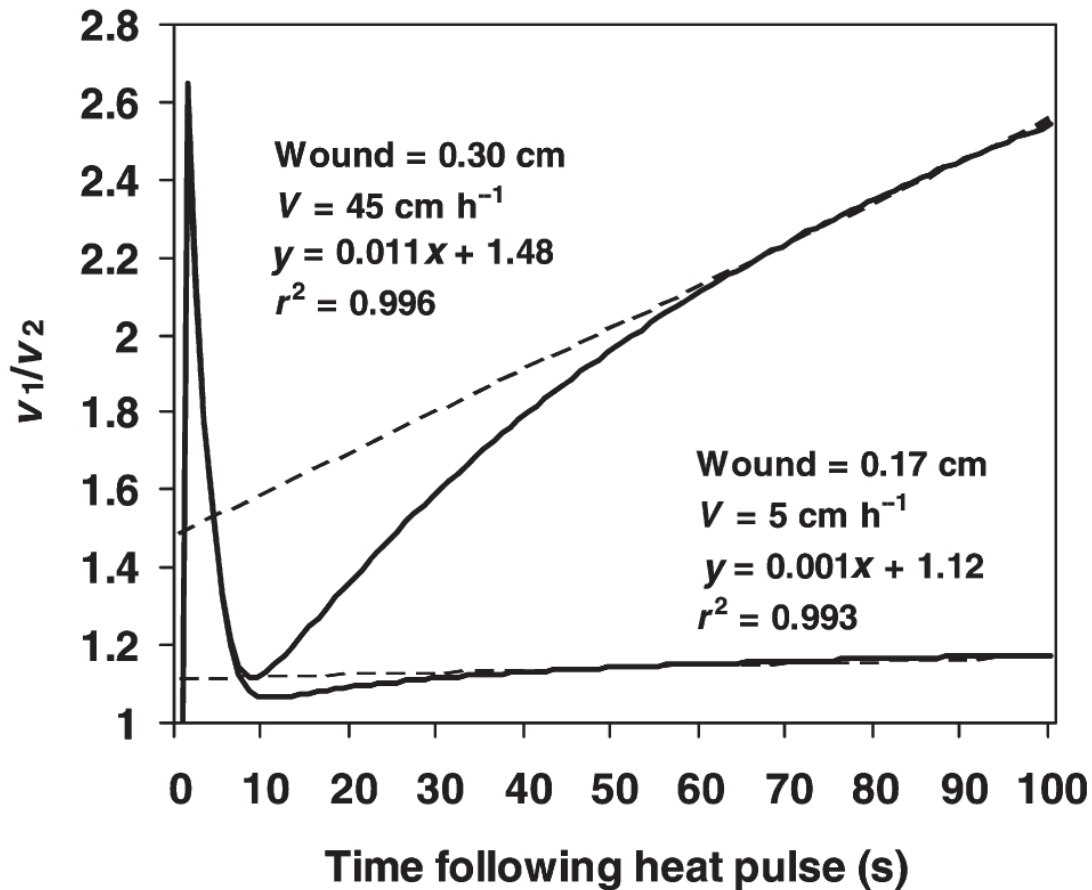


Figure 3. Modelled changes in v_1/v_2 ratios with time for a small wound width (0.17 cm) and low sap velocity (5 cm h^{-1}) compared with a large wound width (0.3 cm) and high sap velocity (45 cm h^{-1}), indicating that v_1/v_2 is essentially linear between 60 and 100 s after the heat pulse (after Burgess et al., 2001).

Data analysis

All available HPV data for an individual tree are initially screened to identify data spikes (outliers) and periods of missing data. Outliers may be removed manually or by applying a smoothing function (e.g. Gaussian) to the data. For gap-filling the first step is to determine if there are good quality data available from any of the other probes for the period in question. Good correlations among different probe sets within the same tree are observed in most cases, and a regression equation is then used to patch the missing data according to the functional probe set. Where there are missing data for all probe sets in a tree simultaneously (e.g. as a result of power disruptions or data-logger failure), data from adjacent measured trees of the same species may be used to correlate and gap-fill. Individual missing hourly data points may be in-filled using an average of the preceding and following values. Automatic weather station data are very useful in interpreting sap flow patterns and assisting in

gap-filling and modelling data gaps unable to be patched using the above approaches.

Once the above analysis is completed, it is necessary to confirm the "zero flux" value (i.e. those times of the day when HPV values / transpiration would be expected to be zero). This is necessary because the lowest values in the diurnal HPV trends (e.g. those values between 22h00 and 04h00) do not always stabilise around zero, due to slight misalignment in the position of the thermocouple probes in the tree. This is corrected by applying an offset to the data. In cases where destructive felling of sample trees is permitted, this correction may be observed by cutting the stem of the tree, while continuing to monitor the zero sapflow condition. Alternatively, for deciduous trees, the "zero flux" value may be determined when the trees are completely leafless, and there is no longer any discernable daily trend in sap flow. Under these conditions the data will typically stabilise around a particular "zero flux" value, which, if not exactly at 0, will indicate the offset value necessary to be applied to the data. However, some species of tree may show reverse sap flow at night (negative night-time HPV values) or actual night-time sap flow (positive night-time HPV values) (Benyon, 1999; Dawson et al., 2007). In order to resolve this, it is consequently necessary to determine the ambient conditions under which "zero flux" is most likely to occur (e.g. pre-dawn, low soil water, high relative humidity). The HPV values at these times may subsequently be adjusted to zero, and the average of these adjustments provides the offset value to be applied to the whole data set (provided the probes were not re-inserted at any point). This procedure therefore does not exclude periods of reverse flow, or night-time sap flow.

The final analysis involves the conversion of the patched and offset hourly HPV values to total daily sap flow (in ℓ and mm). First the hourly HPV values are corrected for the effects of sapwood wounding caused by drilling, using wound correction coefficients described by Swanson and Whitfield (1981) or Burgess *et al.* (2001). These corrected heat pulse velocities are then converted to sap velocities by accounting for wood density and sapwood water content (Marshall, 1958). Finally, the sap velocities are converted to whole-tree total sap flow ($\ell \text{ hr}^{-1}$) by integrating the sum of the products of sap velocity and cross-sectional area for individual tree stem annuli (determined by below-bark individual probe insertion depths and sapwood depth). In this way, point estimates of sap velocity are weighted according to the amount of conducting sapwood they represent. The width of wounded xylem around the thermocouples ("wound widths"), sapwood water content and wood density may be determined from small wood samples, typically taken from the trees at the conclusion of the monitoring period, and incorporating the thermocouple and heater probe insertion holes. The use of tree cores to derive these

variables is not recommended due to wood compression resulting from the coring process. However wood density and water content of small excised wood samples may be determined using oven-dried mass and volume measurements according to Archimedes' Principle. Finally, the corrected sap flow data may be aggregated from hourly values to daily, monthly and annual totals.

Calibration and scaling

Confidence in the results from HPV systems is improved if a reliable independent calibration is performed for each new species in which it is installed; and/or measured heat pulse velocities are related to actual sap flow volumes (Green et al., 2003; Steppe et al., 2010). This is due largely to the fact that the final accuracy of the technique is dependent on a number of parameters mentioned above which may introduce error. Dragoni et al. (2005) used a whole-canopy gas exchange chamber to calibrate sap flow gauges but this requires specialised and expensive equipment and creates an artificial environment around the trees. Other methods that can be used in the field to calibrate the system include the cut stem technique (Olbrich, 1991) or the use of Total Evaporation measurement systems such as Eddy Covariance (Poblete-Echeverría et al. 2012). Data from the latter may be combined with soil evaporation measurements using micro-lysimeters, to estimate transpiration as the difference between the two. However, for comparative purposes sap flow volumes of individual trees first need to be scaling up to forest stands or orchards. This requires sample trees to be as representative as possible of variability within the larger stand or orchard, particularly in terms of the cross-sectional sapwood area and total leaf area of individual trees, as well as the positioning within the landscape (e.g. riparian vs. upland). A number of studies describe appropriate approaches to this (Čermák et al., 2004; Ford et al., 2007; Oishi et al., 2008).

Conclusions

The HRM heat pulse velocity system is useful for estimating transpiration of woody species, and is particularly suited to long term measurements in challenging field situations. The system is reliable, uses fairly inexpensive equipment, has low power requirements and provides sap flow data that correlates well with climatic drivers and other environmental variables, to yield useful estimates of water use. The HRM provides the additional benefit of being able to capture low and reverse rates of sap flow in both stem and roots of suitably sized plants. Provided the necessary steps are taken to reduce measurement error these systems can provide accurate long term estimates of tree transpiration. This obviously requires an understanding of the theory

behind the measurements, the assumptions made, the calibration required, and a pragmatic approach to the challenges of field experiments. Nevertheless, the resultant estimates, extrapolated through modelling can inform wider scale water resource issues through the quantification of water use impacts of different land covers. This information is critically important to water scarce countries such as South Africa, where such information plays a central role in water resource planning and allocation.

Acknowledgements

Long-term financial support from the Water Research Commission over a number of projects where this system was, and continues to be, applied and developed, is gratefully acknowledged, in particular projects K5/1770 (Water use of fruit tree orchards) and K5/1876 (Water use and economic value of the biomass of indigenous trees in comparison with introduced tree plantations) (WRC 2008; 2010). The authors would like to sincerely thank Dr Steve Burgess for sharing the original algorithms and source code on which the technique is based.

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APPENDIX B: ENERGY BALANCE METHODS FOR MEASURING TOTAL EVAPORATION³

Energy balance in the atmospheric boundary layer

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1. Introduction

Net irradiance is the sum of all incoming and outgoing irradiances at the earth's surface (Arya, 2001). For a smooth, horizontal, homogeneous, and extensive surface, net irradiance R_n is the sum of the incoming short wave I_s and long wave L_d irradiances, less the reflected short wave $r.I_s$ and emitted long wave L_u irradiances:

$$R_n = I_s - r.I_s + L_d - L_u \quad (1)$$

and commonly referred to as the radiation balance equation. Net irradiance is the major source of energy for heating and cooling at the surface of the earth and is one of the major components of the energy balance equation.

Micrometeorological methods (eddy covariance, surface renewal, Bowen ratio, scintillometry, and flux variance) used to estimate total evaporation are ultimately based on the energy balance equation, which accounts for all losses of energy that are available for vaporising water. The shortened energy balance equation is expressed as:

$$R_n = G + H + \lambda E \quad (2)$$

³ When making reference to this section, please cite as follows:

Mengistu, M.G. 2014. Energy balance in the atmospheric boundary layer. In: Taylor, N.J. and Gush, M.B. (Eds). 2014. The water use of selected fruit tree orchards (Volume 1): Review of available knowledge. Water Research Commission, Pretoria, RSA, WRC Report 1770/1/14, Appendix B.

where R_n is the net irradiance, G is the soil heat flux density, H is the sensible heat flux density, and λE is the latent energy flux density where advection is assumed to be negligible. For a short and flat surface, the shortened energy balance equation also neglects the energy associated with photosynthesis and respiration, and energy stored in plant canopies as they are usually small compared with the other terms (Thom, 1975). Therefore, the four essential energy fluxes for a short and flat surface are the net irradiance, sensible heat, latent energy, and soil heat flux density if advection is negligible.

The sign convention is that during the day net irradiance is positive with terms on the right hand side of Eq. (2) leaving the earth's surface regarded as positive. The available energy flux density A at the canopy surface (W m^{-2}) is therefore, the difference between the net irradiance and the soil heat flux density:

$$A = R_n - G = H + \lambda E \quad (3)$$

The available energy, $R_n - G$, is equal to the right hand term of Eq. (3), $H + \lambda E$ the turbulent fluxes.

Soil heat flux density, G , is the amount of thermal energy through unit area of soil per unit of time (Sauer and Horton, 2005), and is a function of the change in soil temperature with time and the thermal and physical properties of the soil. The soil heat flux G is estimated as the sum of the flux measured using the soil heat flux plates G_{plate} at a depth of 80 mm and the energy flux stored in soil above the plates G_{stored} :

$$G = G_{plate} + G_{stored} \quad (4)$$

The stored heat flux density G_{stored} is estimated from measurements of the temporal change in soil temperature and the specific heat capacity of the soil above the soil heat flux plate. The stored flux G_{stored} is calculated as (Savage *et al.*, 2004):

$$G_{stored} = \rho_{soil} c_{soil} \Delta z \overline{\Delta T_{soil}} / \Delta t \quad (5)$$

where ρ_{soil} is the bulk density of the soil (kg m^{-3}), c_{soil} is the specific heat capacity of the soil ($\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$), Δz is the soil depth, $\overline{\Delta T_{soil}}$ is the average soil

temperature difference (between 20 and 60 mm) during a measurement interval Δt . The volumetric heat capacity of the soil is calculated as:

$$\rho_{soil} c_{soil} = \rho_{soil} c_{dsoil} + \rho_w \theta_v c_w \quad (6)$$

where c_{dsoil} is the dry soil specific heat capacity ($\approx 800 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$), ρ_w is the density of water (1000 kg m^{-3}), θ_v the volumetric soil water content ($\text{m}^3 \text{ m}^{-3}$), and c_w is the specific heat capacity of water ($= 4190 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$).

The latent energy flux λE (W m^{-2}) is the result of total evaporation, and condensation at the surface and is the product of the specific latent heat of vapourization, λ (in J kg^{-1}) and the water vapour flux density E ($\text{kg s}^{-1} \text{ m}^{-2}$). Latent energy flux density λE may be estimated indirectly as a residual of the shortened energy balance Eq. (2) using sensible heat flux density H , measured net irradiance R_n , and soil heat flux density G as:

$$\lambda E = R_n - G - H \quad (7)$$

Sensible heat flux H (W m^{-2}) is the heat flux which heats the air above the soil and plant canopy surfaces, and arises as a result of difference in temperatures between the surface and the air above. Sensible heat flux may be estimated using different micrometeorological methods, such as eddy covariance, surface renewal, Bowen ratio energy balance, flux variance, and optical scintillation. The eddy covariance and surface renewal methods used in this study for estimating H are discussed in the subsequent sections.

2. Eddy covariance method

In fully turbulent flow, the mean vertical fluxes of heat, water vapour, and momentum can be defined directly in terms of the turbulent (eddy) components of vertical velocities and of the properties being transferred (Rosenberg *et al.*, 1983; Kaimal and Finnigan, 1994). Mean flux across any plane implies covariance between the wind component normal to that plane and the scalar entity of interest (Kaimal and Finnigan, 1994; Arya, 2001).

The eddy covariance (EC) method provides a direct measure of the vertical turbulent flux of a scalar entity of interest F_s across the mean horizontal stream lines (Swinbank, 1951) providing fast response sensors ($\approx 10 \text{ Hz}$) for the wind vector and scalar entity of interest are available (Meyers and Baldocchi, 2005). For a sufficiently long averaging period of time over horizontally homogeneous surface, the flux is expressed as:

$$F_s = \rho_a \overline{w's'} \quad (8)$$

where ρ_a is the density of air, w is the vertical wind speed and s is the concentration of the scalar of interest. The primes in Eq. (8) indicate fluctuation from a temporal average (i.e., $w' = w - \bar{w}$; $s' = s - \bar{s}$) and the over bar represents a time average. The vertical wind component is responsible for the flux across a plane above a horizontal surface. Based on Eq. (8), the sensible heat flux H can be expressed as:

$$H = \rho_a c_p \overline{w'T_s'} \quad (9)$$

where c_p is the specific heat capacity of air, w' denotes the fluctuation from the mean of the vertical wind speed, and T_s' is the fluctuation of air temperature from the mean. The averaging period of the instantaneous fluctuations, of w' and s' should be long enough (30 to 60 minutes) to capture all of the eddy motions that contribute to the flux (Meyers and Baldocchi, 2005).

The *EC* technique, when properly applied, can be used routinely for direct measurements of surface layer fluxes of momentum, heat, water vapour, and carbon dioxide between a surface and turbulent atmosphere (Savage *et al.*, 1997; Massman, 2000; Massman and Lee, 2002; Finnigan *et al.*, 2003). Like other micrometeorological methods, an adequate fetch is required for the *EC* method; a fetch to height ratio greater than 100 is usually considered adequate (Wieringa, 1993).

The *EC* method requires sensitive, expensive instruments to measure high frequency wind velocities and scalar quantities. Besides, eddy covariance data need rigorous quality control and filtering, such as anemometer tilt correction (coordinate rotation, planar fit), spike detection, and trend removal (Meyers and Baldocchi, 2005). Sensors must measure vertical wind speed, sonic temperature and atmospheric humidity with sufficient frequency response to record the most rapid fluctuations important to the diffusion process (Drexler *et al.*, 2004).

3. Surface renewal method

The surface renewal (*SR*) method for estimating H , is based on the idea that an air parcel near a surface is renewed by an air parcel from above. This method is relatively new, attractive and quite simple (Paw U *et al.*, 1995; Snyder *et al.*, 1996; Spano *et al.*, 1997a, b, 2000; Drexler *et al.*, 2004). The

SR method for estimating fluxes from canopies involves high frequency air temperature measurements (typically 2 to 10 Hz) using fine wire thermocouples. The high frequency air temperature fluctuations exhibit organized coherent structures which resemble ramp events (Bergström and Högström, 1989; Gao *et al.*, 1989; Shaw *et al.*, 1989; Paw U *et al.*, 1992). These coherent structures are responsible for transport of momentum, heat and other scalar quantities (Raupach *et al.*, 1989; Qui *et al.*, 1995; Raupach *et al.*, 1996).

The *SR* analysis assumes that the turbulent exchange of air temperature is caused by instantaneous replacement of an air parcel that is in contact with a surface. The parcel heats or cools while it is at the surface because of energy exchange between the air and the canopy elements, then the parcel ejects from the surface and a new air parcel sweeps in to renew the ejected air (Paw *et al.*, 1995; Katul *et al.*, 1996; Snyder *et al.*, 1996; Spano *et al.*, 1997a).

Paw U and Brunet (1991) proposed this model by assuming that under unstable atmospheric conditions when the canopy is warmer than the air, any air temperature increase represents air being heated by the canopy. Under stable conditions, when the canopy is cooler than the air, any air temperature decrease represents air being cooled by the canopy. For a given measurement period, the sensible heat flux density H at any height z is the net exchange of heat associated with all ramps during this period. Paw U *et al.* (1995) expressed H as the change in heat energy content of air with time:

$$H = \alpha \rho c_p \frac{dT}{dt} \frac{V}{A}, \quad (10)$$

where α is a correction factor (regression coefficient fit to the above equation when H is measured independently using other methods such as eddy covariance), dT/dt is the rate of change in air temperature ($^{\circ}\text{C s}^{-1}$) and V/A is the volume of air per unit horizontal area of air. If the air temperature measurement is taken at canopy height, then V/A (which is the vertical distance) will be the canopy height (z_c). High frequency air temperature data are measured at a fixed point and hence the use of Eq. (10) assumes that dT/dt is approximately equal to $\partial T/\partial t$ and internal advection is negligible (Paw U and Brunet, 1991; Paw U *et al.*, 1995). This assumed linear proportionality between the advective term $\partial T/\partial t$ and the total derivative dT/dt has been discussed in detail by Paw U *et al.* (1995). However, this assumption may not be correct under all conditions. For example the assumption may be invalid when there is strong local advection and under high wind shear close to the canopy top of low vegetation and soil surface

(Snyder *et al.*, 1996). Low pass filtering techniques were used by Paw U *et al.* (1995) to smooth the high frequency air temperature data to remove the internal advection and to determine H . However, the filtering technique is cumbersome, due to the necessity of choosing filtering functions and use of numerical methods to identify scalar increases or decreases (Paw U *et al.*, 2005).

When high frequency air temperature measurements are taken at a point at or above the canopy top, ramps are observed in the air temperature traces. These air temperature ramps are characterized by an amplitude $a(^{\circ}\text{C})$, a ramping period L_r (s) where the change in air temperature with time occurs, and a quiescent period L_q (s) for which there is no change in air temperature with time (Snyder *et al.*, 1996; Snyder *et al.*, 1997), as shown in Fig. 1.

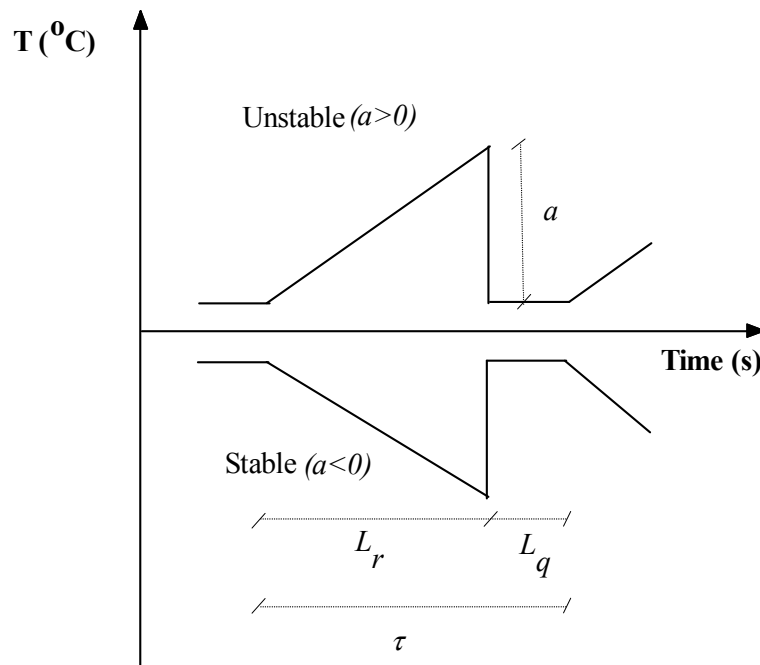


Fig. 1 An ideal surface renewal analysis ramp model, assuming a sharp instantaneous drop in air temperature with amplitude $a > 0$ for unstable and $a < 0$ for stable atmospheric conditions. The ramping period is L_r and L_q the quiescent time period with $\tau = L_r + L_q$ the total ramping period (inverse ramp frequency).

The total ramp duration τ or in other words the inverse ramp frequency is the sum of ramping period L_r and quiescent period L_q . The amplitude a is

positive when the atmosphere is unstable and (the sign of H is positive) and a is negative for stable atmospheres (H is negative).

For estimating H , Snyder *et al.* (1996) simplified and modified the SR analysis by substituting dT/dt in Eq. (10) by a/τ ($^{\circ}\text{C s}^{-1}$) for the average rate of change in air temperature for the total ramping period:

$$H = \alpha \rho c_p \frac{a}{L_r + L_q} z, \quad (11)$$

where α is a weighting factor accounting for the spatially averaged (vertical) air temperature derivative from the bottom to the top of the air parcel (a correction factor for unequal heating or cooling below the sensor). The weighting factor α , depends on z (which is the measurement height), canopy structure, thermocouple size, and the time lag used in the air temperature structure function (Snyder *et al.*, 1996; Duce *et al.*, 1998; Spano *et al.*, 1997a, b, 2000; Paw U *et al.*, 2005). Generally, $\alpha = 0.5$ for coniferous forest, orchards, and maize canopies for measurements taken at canopy height (Paw U *et al.*, 1995). For short turf grass (0.1 m tall), excellent estimates of H were obtained using $\alpha = 1$, when the measurements are taken at 0.35 m and 0.70 m above the turf grass (Snyder *et al.*, 1996).

Snyder *et al.* (1996) used structure functions of air temperature and the analysis technique from Van Atta (1977) to estimate the amplitude a and inverse ramp frequency $\tau = L_r + L_q$. The structure function value $S^n(r)$ is calculated using the relation,

$$S^n(r) = \frac{1}{m-j} \sum_{i=1+j}^m (T_i - T_{i-j})^n, \quad (12)$$

where m is the number of data points in the time interval measured at frequency f , (Hz), n is the power of the function, j is the time lag between data points corresponding to a time lag $r = j/f$ and T_i is the i th temperature sample. Van Atta suggested that, the time lag r must be much less than τ .

An estimate of the mean value for amplitude (a) during the time interval is determined by solving the equation for the real roots.

$$a^3 + pa + q = 0 \quad (13)$$

where

$$p = 10S^2(r) - \frac{S^5(r)}{S^3(r)} \quad (14)$$

and

$$q = 10S^3(r) \quad (15)$$

The ramping period τ is calculated using

$$\tau = -\frac{a^3 r}{S^3(r)} \quad (16)$$

The main advantage of the SR analysis is that only high frequency air temperature data at a measurement height is required to obtain sensible heat flux density. In addition, it is relatively simple and measurements can be easily replicated at a lower cost. The disadvantage of this model is that it must be calibrated using sonic anemometer estimates of sensible heat flux to account for α . The weighting factor α , depends on structure function time lag (Snyder *et al.*, 1996), air temperature sensor size (Duce *et al.*, 1998, cited by Paw U *et al.*, 2005), and the measurement height (Paw U *et al.*, 1995; Snyder *et al.*, 1996). Once the calibration factor α is determined it is quite stable and does not change from site to site regardless of the weather conditions unless there are considerable changes in vegetation canopy structure (Paw U *et al.*, 1995; Snyder *et al.*, 1996; Spano, 2000).

Sensible heat flux density H is estimated based on the high frequency air temperature fluctuations and latent energy flux density λE is obtained as the residual of the shortened energy balance equation.

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