Advances in Irrigation Agronomy

Fruit Crops

M. K. V. CARR

CAMBRIDGE

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As global pressure on water resources intensifies, it is essential that scientists understand the role that water plays in the development of crops, and how such knowledge can be applied to improve water productivity. Linking crop physiology, agronomy and irrigation practices, this book focuses on eleven key fruit crops upon which millions of people in the tropics and subtropics depend for their livelihoods (avocado, cashew, *Citrus* spp., date palm, lychee, macadamia, mango, olive, papaya, passion fruit and pineapple).

Each chapter reviews international irrigation research on an individual fruit crop, identifying opportunities for improving the effectiveness of water allocation and encouraging readers to link scientific knowledge with practical applications. Clearly written and well illustrated, this is an ideal resource for engineers, agronomists and researchers concerned with how the productivity of irrigated agriculture can be improved, in the context of climate change, and the need for growers to demonstrate good irrigation practices.

Mike Carr is Emeritus Professor of agricultural water management at Cranfield University, UK. He has over forty-five years of experience in the management and delivery of international research, education, training and consultancy in agriculture and natural resource management. He is the author of *Advances in Irrigation Agronomy: Plantation Crops* (Cambridge, 2012) and former Editor in Chief of the Cambridge University Press journal *Experimental Agriculture*.

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This book is dedicated to my wife:
Dr Susan Carr
for putting up with me for so long!

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The colour plates are between pages 206 and 207.

Foreword

The last decade has witnessed a partial reversal of the sharp decline in investments in agriculture that occurred all over the world during the previous two decades, due to a false perception among policy-makers that no new investments in food and agriculture were needed. Particularly, since the dramatic increases in the price of food in 2008, agriculture is back on the global agenda and will remain there for years to come. Population growth and economic development are the driving forces behind demands for increased food production and for a more diversified diet. World production of fruits and vegetables has proportionally increased from 18 to 23% of the total agricultural output over the last nine years. Driven by efficient transport systems and by the advances in post-harvest technologies, and facilitated by globalisation, the diversity of fruits now being offered to consumers in world markets has expanded enormously. Barriers of space and time no longer exist for accessing fresh fruits at any season, and the only limits are imposed by economics. Growing high-quality fruits successfully is at the starting point of this new development in the diversification of the human diet.

Modern advances in agriculture have been founded on agricultural research, and fruit production is no exception. However, much of the research has been carried out on temperate species such as the apple, and much less effort has been devoted to study the performance of fruit crops grown in subtropical and tropical environments. The increased popularity of exotic fruits demands that much more attention is paid to tropical fruit crops and their production processes. Water management is essential for stability of production in such environments and this book represents an important effort towards optimising the agronomy of irrigation in these species. The book is second in a series on irrigation agronomy, the first having focused on plantation crops.

The author of both books, Professor Mike Carr, has had an extensive career, first in the tropics for many years and, subsequently as professor of agricultural water management at Cranfield University, UK. Plucking through the ever-expanding body of literature (a term commonly used in tea harvesting, his favourite crop), Professor Carr has selected the best ‘sprouts’ (among a vast sea of literature of varied relevance) to produce a superb synthesis of what is known on irrigation and water relations of the principal subtropical and tropical fruit crops. He has also managed to identify the major gaps in knowledge (and the duplication of efforts in some cases), providing insight into what research will be needed in the future. There is a unifying line of thought throughout the book, as the author aims at connecting the fundamental knowledge to the relevant applications in irrigation management, with the goal of providing the necessary elements that field practitioners need for precision irrigation. Mike Carr has produced a book that will have a significant influence on the development of the tropical fruit industry, as well as among a new generation of irrigation scientists, which is badly needed to meet the challenges that irrigation will be facing in the future.

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Also Editor-in-Chief *Irrigation Science*
Cordoba, June 2013

Preface

This is the second book in a series published by Cambridge University Press under the generic title ‘Advances in Irrigation Agronomy’. The first focused on the water requirements and water productivity of nine plantation crops grown in the tropics or subtropics on which millions of people from around the world depend for their livelihoods. They included several tree crops, such as rubber, cocoa, coffee and tea, two palms (oil palm and coconut), a giant herb (banana), a succulent xerophyte (sisal) and a grass (sugar cane). This diverse range of crops has an equally diverse range of useful products from latex to sucrose, to oil, to fibre, to leaves, to fruit, to seed.

When the book was completed someone immediately said ‘why didn’t you include *Citrus* spp., after all they are plantation crops too?’. That question immediately raised another question; where are the boundaries between orchard crops and plantation crops? After all, two fruit crops, banana and coconut, had been included, and the useful products of two others, oil palm and cocoa, come essentially from fruits. To build on what had gone before, and to fill some gaps, the next book in this series had to be about fruit crops. So this book is about fruit crops that are grown commercially in the tropics and subtropics (broadly defined), for export, as well as for local consumption. Following improvements in post-harvest storage and transport systems, there is now an increasing international demand for exotic fruits. One reviewer asked another fundamental question: ‘how was it decided which crops to include (or to exclude)?’. Since there was an element of subjectivity in making that choice, depending in part on the geographic and other limits that were set, this was not an easy question to answer. Hopefully you will find that the selected crops are representative of the major fruits produced in the tropics and subtropics. But, inevitably, not all the important, or potentially important, crops could be included. This issue is considered further in Chapter 1.

On a personal note, after graduating from Nottingham University in the UK, I had three rewarding, and overlapping, roles as a university teacher, a researcher and an adviser in agriculture, with irrigation water management as a common theme. Each one of these roles took me overseas, with professional visits to over 30 countries in the tropics and subtropics. These included Tanzania and Kenya, where we lived for five years, other countries in east, west and southern Africa, at both low (Nigeria) and high altitudes (Uganda), the Indian subcontinent, from Sri Lanka to Bangladesh, Central America (Mexico), South-east Asia (Indonesia and Malaysia); the far east (Japan), western Asia (Israel, Iraq, Jordan), western and southern states in the USA and deserts (in Israel and Nigeria), as well as Mediterranean basin areas and temperate regions throughout Europe. Since retiring, I have been able to extend my international experience with visits to Australia, New Zealand and China.

My birth certificate describes me as the son of a smallholder. Growing up on a farm provided me with an understanding of the day-to-day challenges faced by families relying on the land to provide their livelihoods, and their dependency for survival on the weather. The common theme in my career has been to try to facilitate effective communication of the outcomes from research to the stakeholders, whoever they are and whatever status they occupy. I have been privileged to live, visit and work in some beautiful places alongside committed and talented people from whom I have learnt a lot. I have witnessed crops of all types being grown in diverse farming systems, from the very primitive to the very sophisticated, in areas receiving less than 200 mm of rain annually to those with more than 2500 mm, from small-scale, labour-intensive irrigation of individual trees with water from a bucket, to large-scale, automated centre-pivots applying water to more than 60 ha in one rotation.

This, therefore, is the background from which I have come and from which this book has evolved. Each of the 11 core chapters covers one fruit crop. These are grown by smallholders as individual trees, or in small orchards, as well as by commercial companies in large-scale plantations. As background information, each chapter begins with a description of the centre of origin of the crop, and the most recent (at the time of writing) production figures. This is followed by a summary of the development stages of the plant in the context of water availability, fundamental plant–water relations, crop water requirements and water productivity, and finally irrigation systems and scheduling (where appropriate). Each chapter is designed to contribute towards converting science into practice by bringing together and interpreting information from a diverse range of sources (over 600 references have been accessed and cited). All the chapters follow a common format, and include interim summaries, together with recommendations on the outstanding researchable issues. In addition to the core chapters, there is an introductory chapter at the beginning of the book, and a synthesis at the end.

Each chapter is based on a paper that has already been published in *Experimental Agriculture* (or is in press), an established refereed journal published by Cambridge University Press. The crops covered are avocado, cashew, citrus, date palm, lychee, macadamia, mango, olive, papaya, passion fruit and pineapple. Cross-references are made, where appropriate, to the reviews of banana and coconut published in Volume 1. My hope is that people from a wide range of backgrounds will find this book as useful and as interesting as I found it to research and write.

Acknowledgements

Once again I have had the help and support of many people whilst compiling this book. I begin by thanking my wife, Susan, for tolerating my self-indulgence over many months, and for reading and constructively editing each chapter with great skill.

Each of the core chapters is based on a paper that has been published in the Cambridge University Press's international journal *Experimental Agriculture*. I acknowledge with thanks the skill with which the editor, Dr David Harris, handled the peer-review process. Anonymous referees provided helpful feedback. This is a thankless, unrewarded but essential task that underpins the reputation of academic journals. I cannot think of any other profession that would undertake such a task without demanding payment.

Individuals, who are recognised as leaders in their fields also helped by reading and providing expert advice on how to improve draft versions of each chapter. These include: Professor Ahmed Al-Amoud (date palm), Dr Duane Bartholomew (pineapple), Professor Elias Fereres (olive), Dr Wayne Hancock (macadamia, mango and papaya), Dr Emi Lahav (avocado), Dr Rob Lockwood (citrus and macadamia), Dr Chris Menzel (co-author of Chapter 6, lychee), Professor Robert Paull and Peter Rigden (passion fruit), Dr Russ Stephenson (macadamia) and Dr Clive Topper (cashew). General advice was always available from Dr Hereward Corley, Melvyn Kay, Dr Rob Lockwood and Dr David Midmore. But, needless to say, any mistakes are all mine!

Professor Elias Fereres, Editor-in-Chief of *Irrigation Science*, kindly wrote the Foreword. I first met Elias in a peach orchard in Davis, California in 1978, when we were both much younger!

Photographs came from a number of sources. Many were selected from the collection of slides belonging to the late Professor Don Tindall, previously a colleague of mine at Cranfield University, UK. I am sure that he would be pleased that his slides have been retained and put to good use. Don's pictures are labeled HDT in the text. Photographs have also been generously provided by Richard Carter (RCC), Colin Congdon (TCEC), Elias Fereres (EF), Susan Hayden (SH), Luiz Mirisola (LM), Raffi Stern (RS) and myself (MKVC). John Shepherd kindly prepared some of the images for publication.

Staff of the Cambridge University Press were supportive throughout the publication process, particularly Megan Waddington (Editor – Life Sciences) and Dominic Lewis (Commissioning Editor – Life Sciences). I thank them both. Jo Tyszka was an excellent copy-editor.

1 Introduction

The introduction is divided into three sections: in Part I, *Background*, the reasons for writing this book, and the purposes it is intended to serve are described. The geographic areas in which fruit crops are grown are defined and the reasons for the selection of particular crops to be reviewed are explained, including their origins and centres of production. The principal farming systems in which fruit production is a component are briefly summarised, with a focus on the continuing intensification of crop management practices. Finally, the role that irrigation of fruit crops can play in the sustainable production of high-quality fruit is outlined, providing enough water is made available for irrigation in water-scarce areas of the world. Part II provides a synopsis of the basic science behind *Understanding Crop Productivity*, including measurement techniques. In order to provide a comprehensive account within this book, it largely repeats the corresponding section in Volume 1.[1] Topics covered include crop development stages, plant–water relations, crop water requirements, and water productivity. Finally, Part III provides a description of the main *Irrigation Systems* used to irrigate fruit crops, and the principal methods recommended to growers on how best to schedule irrigation.

PART I: BACKGROUND

There are few easily identifiable or accessible sources where the results of international irrigation research have been brought together and interpreted in coherent and useful ways for individual crops. This is in part due to the diversity of sources, and also to the difficulty of reconciling the results of research conducted in contrasting situations, often with insufficient supporting information to allow the results to be extrapolated to new situations with confidence.

A scientific understanding of the role that water plays in the growth and development of crops is essential, but this knowledge needs to be interpreted and presented as practical advice in a language that can assist planners, irrigation engineers, horticulturalists and producers to allocate and use water, whether from rainfall or irrigation, effectively and profitably. Communication between the professions attempting to improve irrigation water management for the benefit of the commercial producer and the wider community can always be improved. Field experiments must be well designed and managed to quantify with precision the (marketable) yield responses of crops to water (Carr, 2000). Adequate supporting measurements need to be taken to enable the results to be interpreted and applied with confidence to other locations, or at other times, where the climate, weather and/or soils may be different. Site-specific, single-discipline, empirical studies should normally be avoided. *But, to minimise duplication of effort, existing information on the water relations and irrigation needs of individual crops first needs to be collated and interpreted in practically useful ways*. This is especially true for orchard crops having international commercial importance. This is what this book sets out to achieve. It follows the first book in this series, which was devoted to plantation crops. Fruit crops, in particular those grown in warmer regions of the world, tend to be neglected in review books. For example, in the comprehensive reference text *Irrigation of Agricultural Crops* only deciduous trees were included (Stewart and Nielsen, 1990), and only three evergreen subtropical fruit crops (avocado, citrus and olive) were reviewed in the FAO Irrigation and Drainage Paper 66 *Crop Yield Response to Water* (Steduto *et al*., 2012).

Reasons for writing this book

Average yields of all orchard crops, and even the best commercial yields, are often still far below the potential yields. Water is just one of many limiting factors, but in some locations it is the major one. One purpose of this book is to collate all the published information on the water relations of the important orchard crops in order to quantify, where possible, the yield losses due to water stress or, where appropriate, the likely benefits from irrigation or other approaches to drought mitigation as an aid to planning. Another purpose is to provide an entry point for researchers wishing to build on what is already known and avoid duplication of effort. A third purpose is to compare and contrast different orchard crops since, because of specialisation and regional diversity, there is often limited cross-fertilisation of knowledge about other crops among researchers and producers. A fourth purpose is to make a contribution to the need, frequently stated, to use water more productively in the face of increasing competition for a scarce resource (Perry *et al*., 2009; Perry, 2011). The uncertainties associated with climate change make water productivity even more of an imperative (Corley, 2012). Finally the book is intended to be a source of reference for students wishing to know more about tropical and subtropical horticulture and its continuing but rewarding challenges.

Definitions

Sampson (2003) defined fruit growing simply as ‘the cultivation of edible fruits that are consumed either fresh or processed’. A fruit is the structure that develops from individual flowers or from inflorescences, usually after fertilisation. In most cases the marketed fruit consists only of the developed ovary, but it may include other parts of the flower such as the receptacle (part of the flower stem; e.g. *apple*). A *pineapple* is formed from a cluster of flowers that have fused together; it is known as a multiple or aggregate

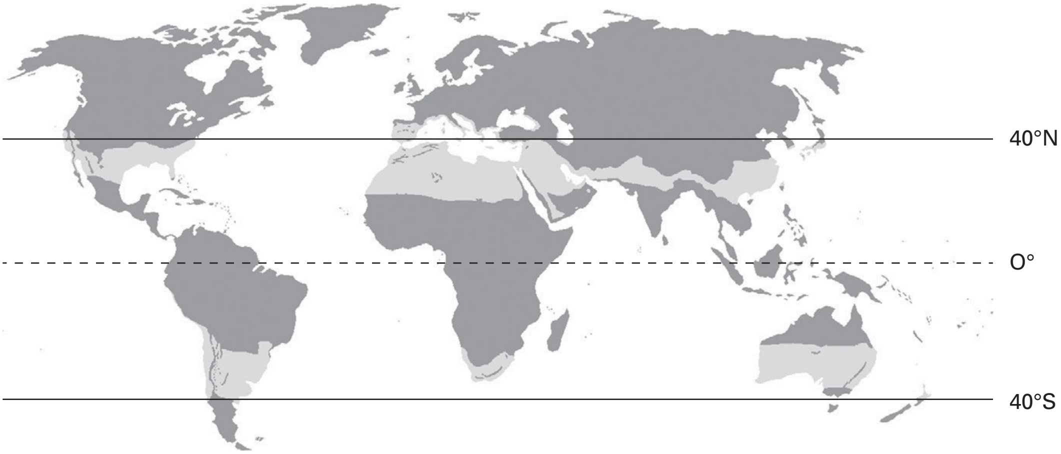

Figure 1.1 World map showing the official limits of the tropics and subtropics, including the Mediterranean-type areas.

fruit. Some fruits are eaten as vegetables (e.g. tomato), but most are normally eaten fresh and out of the hand, although there are many exceptions. A nut is a type of fruit.

Although fruit crops are often divided into those that are grown in the tropics, the subtropics and the temperate regions of the Earth, it is not always easy to make this distinction. There is a great deal of overlap in the geographic areas where these crops are grown commercially. This classification is unrelated to the regions of the world in which individual crops are believed to have originated. The boundaries between the Tropics of Cancer and Capricorn (23°27’ north and south of the Equator) are too rigid to be a useful guide to the areas suitable for growing tropical fruit, as they contain high-altitude areas, where crops considered to be best suited to the subtropics or even to temperate regions can be grown successfully. Similarly, there are areas beyond these boundaries that have local or regional climates where crops associated with the tropics can be grown. The subtropics officially refer to the regions beyond the boundaries of the two tropics up to about 40°N and 40°S latitude (Figure 1.1). In addition there are areas with what is known as a Mediterranean-type climate, which can also be described as subtropical (Anonymous, 2012).

The Mediterranean Basin has long been a site of subtropical and temperate fruit production. It embraces southern Europe, northern Africa and parts of Western Asia. Similar climates are also found elsewhere in the world, for example, in much of California, in parts of Western and South Australia and northern New Zealand, in south-west South Africa, sections of Central Asia and in parts of central, coastal Chile. The reason for these similarities in climate across diverse areas of the Earth’s surface is due to their association with five, large subtropical high-pressure cells linked to the oceans.[2]

The tropics, subtropics, Mediterranean and temperate areas differ climatically in terms of temperature (absolute level, variability during the year, and differences between night and day), the dryness (saturation deficit) of the air, incoming solar radiation levels, hours of daylight, and total rainfall and its seasonal variability. In the low-altitude humid *tropics*, there are usually two rainy seasons separated by two dry, or less wet, periods. Here there may be a need in some years to supplement rainfall with irrigation. Temperatures vary little during the year, averaging about 27 °C. In semi-arid, *subtropical* areas, there is usually a short rainy season, followed by a long dry season when supplementary irrigation of fruit crops may be necessary or even essential depending on the crop, the season and the amount of rainfall and its timing. Here the summers are hotter and the winters colder than in the humid tropics. The subtropics are bounded by the 10 °C isotherm in the coldest month. In the *Mediterranean-Basin-type climate areas*, there is rain during the mild to cool winter whilst the summers are warm to hot, and dry. Crops that are not irrigated usually survive the summer on the surplus winter rainfall stored in the soil. In the extreme climate conditions that are associated with *deserts*, irrigation (or a high water-table) is essential for any form of crop production. But irrigation does not always substitute for rainfall. For example, dry air can inhibit crop growth processes even when the soil is wet (although high levels of solar radiation in the dry season may more than compensate for the adverse effects of dry air) (Figure 1.2).

The *temperate areas* extend from about 40°N and S to 66°N and S and can be divided into *maritime regions* (temperatures stabilised by the proximity of the oceans) and *continental regions* (more extreme winter and summer temperatures) that can be semi-arid or arid. In maritime regions, rainfall can be expected throughout the year, but there is great variability from day to day, from month to month and from year to year. Here irrigation is supplementary to the rainfall, providing stability in production.

Figure 1.2 An oasis in north-east Nigeria bordering Niger. The date palm (*Phoenix dactylifera* L.) (together with the branched doum palm (*Hyphaene thebaica* L. Mart)) relies on a shallow water table (or irrigation) for survival in these arid areas (MKVC). See also colour plates section.

Which fruit crops to review?

In the tropics, the most important perennial fruit crops, based on quantities harvested, are *banana* (with *plantain*), *mango*, *coconut*, *papaya* and *pineapple*. They are all well known in both local and international markets. Those of lesser international importance, such as *passion fruit* and *cashew* nuts, are now attracting more attention and expanding in importance. Most of these crops are trees, the exceptions being *banana*/*plantain* and *papaya* (large herbs), *pineapple* (herb) and *passion fruit* (vine). Extending into the subtropics are *orange* (*citrus*), *lychee*, *avocado* and *macadamia*. With the exception of *banana* and *coconut*, all these crops were chosen for inclusion in this book in part because of their biological diversity as well as their popularity. *Banana* and *coconut* were covered in Volume one of this series on plantation crops, but are considered here alongside the other fruit crops in the Synthesis (Chapter 13) (Figure 1.3). There are of course many other tropical fruits of considerable economic importance in their respective regional markets, but of lesser international importance. These include *carambola*, *rambutan* and *mangosteen*, seedlings of which may take 15 years to produce a profitable crop (Figures 1.4, 1.5 and 1.6) and the unusual *jackfruit* (Figure 1.7). All of these are indigenous to South-East Asia. There is also the *pejibaye* palm, about which little is known outside northern South America and Central America. All of these crops are under-researched, and that is one of the reasons that they are not reviewed here (NAS, 1975; Wickens *et al*., 1989).

Olive, *peach* and *apricot* (all of which are trees) are fruit crops that are normally associated with a subtropical Mediterranean-type climate. Of these, only the *olive*, an

Figure 1.3 Coconut (*Cocos nucifera* L.): an inflorescence is initiated up to 44 months before the fruit is harvested – Tanzania (MKVC).

Figure 1.4 Carambola (also known as star fruit) is the fruit of *Averrhoa carambola* L., a species of tree native to the Philippines, Indonesia, Malaysia, Indonesia, India and Sri Lanka – Malaysia (MKVC).

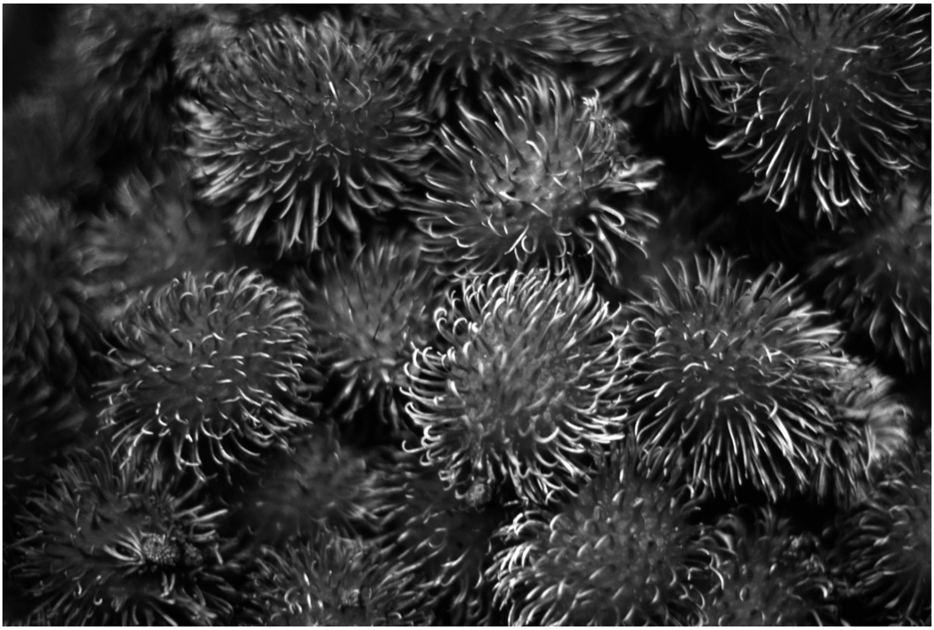

Figure 1.5 Rambutan (*Nephelium lappaceum* L.) is native to Indonesia and Malaysia, and is a relatively common crop in South-east Asia The word 'rambut' refers to the spiky rind. Rambutan is related to the lychee (Chapter 6) – Thailand (HDT). See also colour plates section.

Figure 1.6 The purple mangosteen (*Garcinia mangostana* L.) is a tropical evergreen fruit tree believed to have originated in the islands of Indonesia. It is grown principally in South-east Asia and more recently it has been introduced into South America – Thailand (HDT). See also colour plates section.

example of a well-researched crop grown extensively (and now intensively) in southern Europe, is reviewed here. Also reviewed is the *date palm*, a crop that is linked with the unique oasis farming systems found in North Africa and West Asia on the opposite shores of the Mediterranean Sea.

Well-known temperate crops include *apple*, *pear*, *apricot*, *quince* (all of which are trees), together with the *grape*, a traditional source of wine, and the *kiwi*, a twentieth-century crop (both vines) (Figure 1.8). No temperate crop is included here. Small fruits such as *strawberry*, *raspberry* and *currant* are also not covered.

The tropical and subtropical crops described are all evergreen (senescing leaves are continuously replaced), although *avocado* is strictly classified as winter-green because the longevity of the leaves is no more than 12 months, and the entire leaf canopy is replaced in two to three weeks during the renewal spring growth that comes after flowering. By contrast, some Mediterranean-type and most temperate crops, including *peach*, *grape* and *apple*, are deciduous (Figures 1.9 and 1.10). Deciduous crops begin to shed their leaves in the autumn as temperatures fall. The buds then enter a state of dormancy (known as a 'rest period'). Dormancy is broken and refoliation begins after the buds have experienced a period of cold weather. One method used to calculate this 'winter chilling requirement' is to count the number of hours that the air temperature is at or below, for example, 7 °C. Another consideration affecting where a crop can be grown is the level of frost it can withstand, and its susceptibility to water stress. Most of the crops described here are mesophytes

Figure 1.7 Individual fruits of jackfruit can weigh up to 30 kg and a productive tree can produce up to 200 fruits a year – Uganda (RCC). See also colour plates section.

(adapted to average moisture conditions), but three xerophytes (adapted to dry conditions) are also included: *date palm*, *olive* and *pineapple*.

Galán Saúco *et al.* (2012) have highlighted the difficulty of formally differentiating subtropical fruit crops from those predominantly grown in the tropics. Indeed they have argued that more tropical crops could be grown in the subtropics, given sufficient research effort. For example, *avocado*, *lychee* and *mango* have already become important commercial crops in many subtropical countries after many years of research and the effort of growers. Other potential examples include *banana*, *guava*, *passion fruit* and *carambola*. Galán Saúco *et al.* (2012) suggest that there are a number of advantages to be gained by growing tropical crops in the subtropics. These include: less vigorous vegetative growth due to cooler conditions (at least in winter) would mean easier canopy management and tree training, which in turn could mean higher planting densities, with larger initial yields; proximity to the market (cost saving, reduced carbon

Figure 1.8 Kiwifruit is the edible berry of a woody vine (*Actinidia chinensis* Planch.). It is native to southern China, and was introduced into New Zealand in the early twentieth century, where it was developed into a commercial crop. It is now grown in more than ten countries, principally Italy, New Zealand, Chile and Greece – Thailand (HDT).

Figure 1.9 Peach (*Prunus persica* L. Batch.) is a deciduous fruit tree native to China. It sheds its leaves in the autumn and flowers early in the spring before re-foliating. Fruit are produced during the summer – Israel (MKVC).

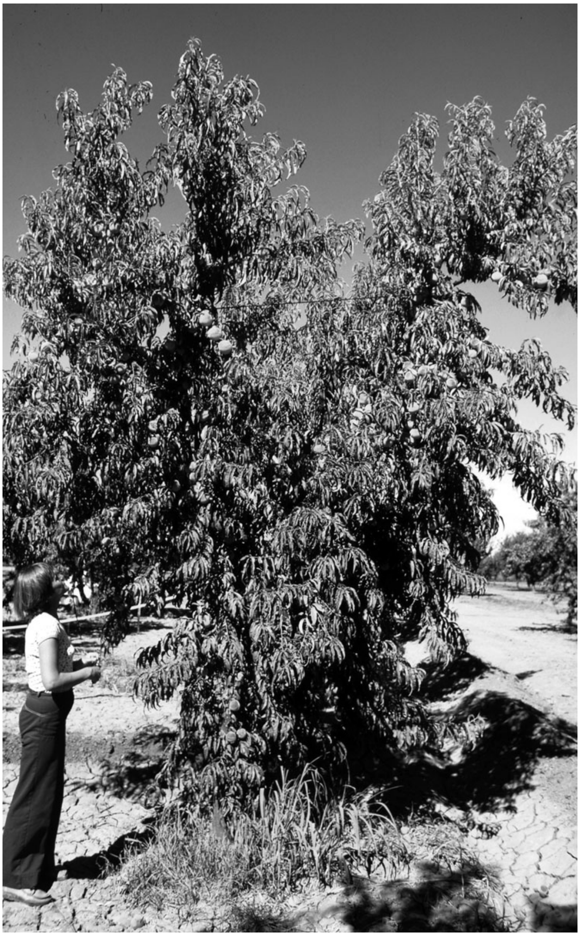

Figure 1.10 A fully foliated peach tree with fruit in California (MKVC).

footprint) and reduced risk of pests due to constraints of low temperatures in winter. Disadvantages include: pest and disease risks (e.g. weever borer and Fusarium wilt in banana) and damage by low temperatures.

These land-use changes are already taking place in the Mediterranean Basin. For example, in one small but representative watershed in south-east Spain, many of the long-established rain-fed orchards have largely disappeared. Over a 30-year period (1978–2007), traditional hand-cut terraces, built of stone, producing rain-fed crops (in 1978: 64% of the area was *almond*, 7% *vines* and 2% *olive*, plus 25% fallow) had become mechanically constructed, reverse-slope bench irrigated terraces producing tropical/subtropical crops (in 2007:19% *avocado*, 17% *almond*, 4% *mango*, 2.4% *loquat*, 1% *cherimoya* and 0.6% *vines*; in addition, 55% of the land had been effectively abandoned). This shift towards intensively grown, subtropical crops may or may not be sustainable (Zuazo *et al.*, 2011a). Similar changes are happening in Israel.

Centres of origin and production

Most of the best known tropical and subtropical fruit crops originated in the equivalent climatic regions of South America (for example, *avocado*, *papaya* and *pineapple*), in Asia (for example, most Citrus fruits, *mango*, *banana* and also *lychee*) or in Oceana (*coconut*, in the Pacific Islands, and *macadamia*, in Queensland, Australia). *Date palm* is believed to have originated in West Asia. Soon after Europeans 'discovered' the Americas, there was an exchange of plant species between the regions: for example, *pineapples* and *cashew* travelled east, whilst *Citrus* and *mango* went west. This coming together of the two hemispheres after millions of years of separation had profound ecological and cultural implications, not least through the transfer of crops (Mann, 2011).

Figures 1.11 and 1.12 show the centres of origin and current centres of production of the fruit crops reviewed here. Many fruit species provide other products apart from food, including timber, furniture, shelter, clothing, fuel, alcohol and medicine, and these uses have contributed to their spread and adoption across the world, as has the ease with which they can be propagated. By contrast, *mangosteen*, *rambutan* and *durian* have remained close to their areas of origin in South-east Asia. Since the 1970s, demand for the fruits of tropical and subtropical crops such as *avocado* and *mango* has increased in the so-called developed world, following improvements in transport and post-harvest storage systems. These fruits are no longer considered to be exotic (Figure 1.13).

This expansion of markets is a continuing process. For example, an up-and-coming tropical fruit with an expanding international market is *persimmon* (from China). By contrast, *apple* and *peach* are long established as internationally traded crops. *Apple* is believed to have originated in Kazakhstan and neighbouring Central Asian countries, whilst *peach* is also native to China. These two crops are now grown throughout the

Figure 1.11 World map showing the centres of origin of fruit crops covered in this book.

Figure 1.12 World map showing the principal areas of production of the fruit crops described in this book.

Figure 1.13 Pineapples for sale in a supermarket in Beijing, China (MKVC). See also colour plates section.

temperate regions, in parts of the subtropics, and at high elevations in the tropics. Because *peach* is more susceptible to frost than *apple*, its geographic range is limited.

Production systems

To differentiate tree crops from forestry, tree crops must, by definition, produce a regular crop that has marketable and/or nutritional value to the farmer (Figure 1.14). Fruit trees meet these criteria. Topper and Caligari (2003) have written at length about the multi-faceted role of tree crops, including fruits, in the economic development process. Fruit crops are grown under one of two, usually distinct, systems: family-run smallholdings or professionally managed orchards/plantations (Figures 1.15 and 1.16).

The degree of commercialisation varies considerably among smallholders, from farming purely for subsistence, through production for the home and local markets, to

Figure 1.14 Tapping for palm wine in Sierra Leone; palm trees can be a source of alcohol (RCC). See also colour plates section.

Figure 1.15 A small mixed rain-fed farm in Kenya with fruit trees (papaya and citrus) and arable crops (*Phaseolus* beans and maize) – (MKVC). See also colour plates section.

Figure 1.16 An example of a modern, intensive, hedgerow pear (*Pyrus communis* L.) orchard in New Zealand (with plastic cover) – (MKVC). See also colour plates section.

production for a regional or export market, or for sale to local processing factories (e.g. for canning and juice). The relative importance of these two systems varies greatly from country to country (indeed also within a country), and from crop to crop. For example, in Tanzania *cashew* is predominantly a smallholder crop, whereas in neighbouring Mozambique the estate sector has played a much larger role in its production. In Thailand, 95% of all *pineapple* producers are small farmers with holdings of 1–5 ha, but in the Philippines and Indonesia large plantations predominate (>20 000 ha each).

Intensification

> ‘*From the earliest times trees have formed part of man’s environment providing him with sources of raw materials, food and drink. The first exploitations were of trees growing in the wild, but gradually over the centuries the most useful species have been brought into cultivation and grown as crop plants. By breeding and selection, improved strains have been developed, methods of propagation worked out and, largely by trial and error, the most suitable cultural conditions for each species have been discovered. Although such empirical methods have served us well in the past we are now approaching the stage when further major advances in the culture of tree crops will demand a much greater understanding of the physiology of woody perennial species*.’

This perceptive quote comes from the Preface to a book published in 1970 entitled *The Physiology of Tree Crops*, in which the proceedings of a conference of the same name were reported (Luckwill and Cutting, 1970). How relevant is it still today?

Our scientific understanding of the ways trees grow has increased considerably since 1970. The application of increased knowledge has led to the intensification of management practices. In the case of fruit trees, recent advances include higher tree densities (for example, traditional *olive* orchards were planted at densities of fewer than 100 trees ha^{-1} whereas a modern, irrigated plantation would have 500–1000 trees ha^{-1}, or even more), new methods of canopy management (training and pruning), including hedgerow-fruit production systems, to improve light interception and conversion efficiencies, new cultivars (and rootstocks) and the opportunities that micro-irrigation systems offer to growers to apply small quantities of water at short intervals (with fertiliser). But, as Palmer (2011) has pointed out, understanding the production system within the orchard in order to improve carbon acquisition and distribution to the fruit is no longer enough. Consumers, retailers and governments want to know the energy costs and carbon footprint of the whole production and distribution system, and that includes *water productivity*, a term which essentially means ‘the amount of yield produced per unit of water used’, see below (Morison *et al*., 2008).

Irrigation

The important role that water plays in the production of fruit crops has been well described by Fereres and Evans (2006) in the introduction to a special issue of *Irrigation Science*.

As demands on the world's freshwater supplies grow, the transfer of water from agriculture to other sectors will become more and more common. The irrigated agriculture and horticulture community will need to be able to justify the ways in which they use water if they are to compete with the demands of other industries, municipalities, domestic consumers and the environment. This will involve convincing others that best practice is being observed in the orchard and on the farm, judged against agreed benchmarks for the water productivity of individual crops, probably expressed in financial terms.

Irrigation of fruit crops not only provides some security in protecting a large investment, but also increases and stabilises production from year to year. Cumulative benefits can also be expected over time, especially in the early years following planting (Goode, 1970). Crop quality can be improved, leading to better prices (Carr, 1981). But, as Fereres and Evans (2006) point out, the majority of growers still manage irrigation applications on the basis of either rigid calendars, determined by external factors such as rotation delivery schedules or, at best, on qualitative observations. Irrigation scheduling based on good science requires an estimate of crop water use, knowledge of how crops respond to water stress and a method for detecting when to irrigate. Effective scheduling takes time and effort, and some knowledge of the complicated relationships between soil, plant and water. If the benefits are not always immediately obvious to the grower, it is not surprising that few growers/farmers around the world persist with using scientific scheduling methods.

Modern irrigation practices for fruit trees were developed in California between 1910 and 1940 on deep valley soils with large water-holding capacities. These soils facilitated deep rooting thereby buffering any inaccuracies in scheduling or non-uniformity in water application (Uriu and Magness, 1967; Hilgeman and Reuther, 1967). The advice given to fruit growers in California 50 years ago on irrigation and cultivation of orchards makes interesting reading today (Veihmeyer and Hendrickson, 1960). Many of the principles still apply. Orchards that have been established recently in areas with favourable micro-climates (e.g. for earliness) may have soils with low water-holding capacities that require more sensitive methods for deciding when to irrigate, and how much water to apply, compared with the deep soils found in the California Central Valley. Such soils need precise ways of applying small quantities of water at frequent intervals uniformly across the orchard. There is also public pressure to conserve water, considered by many to be a scarce resource – though perhaps it would be more accurate to say 'clean, fresh water is a scarce resource'. This has all led to the concept of 'regulated deficit irrigation' (Fereres and Evans, 2006). This practice, which is perceived to be new, but in fact goes back a long way (Salter and Goode, 1967), aims to reduce water use by imposing water deficits at certain developmental stages of growth without causing a proportionate loss in yield. That is, the water productivity is increased. This concept of regulated deficit irrigation has been extensively researched (in both good and bad experiments) with many of the main fruit crops (principally temperate) over the last 10–20 years.

PART II: UNDERSTANDING CROP PRODUCTIVITY

For most of the crops considered here, the fruit is the principal useful product, although other parts of the plant/tree may also have a value. An extreme case is the *coconut* palm, the so-called ‘tree of life’, in which nearly the whole tree contributes something to livelihoods, although the primary product is copra (for oil). The *date palm*, *cashew* and *pineapple* also provide many useful products in addition to the fruit itself (as does the *doum palm*, Figure 1.17). In considering ‘crop productivity’ the focus will be on the fruit itself.

Crop development stages

The yield of any crop (Y) can be considered in terms of the efficiency of successive stages in the conversion of solar energy (S) to the economic or useful product. Thus:

$$Y = S \times f \times e \times HI$$

where S is the total solar energy received at the surface of the crop, f is the fraction of the energy intercepted by the leaf canopy, e is the conversion ratio (or efficiency) of solar radiation to dry matter and HI is the ratio of energy in the economic product to

Figure 1.17 Palms have many ancillary products in addition to their fruit. Here, a Fulani cattle herder in northern Nigeria is seen weaving the fibres taken from a doum palm (*Hyphaene thebaica* L. Mart.) and creating ropes, mats, baskets and hats – (MKVC). See also colour plates section.

the total energy fixed by the crop (or in non-oil-bearing crops the dry matter ratio is often used instead of energy). Typical annual incident solar radiation totals range from around 55 TJ ha^{-1} in the high-rainfall areas in Bangladesh and Assam, to 63 TJ ha^{-1} in fruit growing areas of Malaysia, to 70 TJ ha^{-1} in parts of East Africa with clear skies during long dry seasons (Monteith, 1972).

The leaf area required to intercept a given proportion of solar radiation depends largely on the canopy geometry. Crops with erect leaves held in clumps (e.g. *palms*) require a larger leaf area index (L) to intercept a given proportion of radiation than those with horizontal, uniformly spaced leaves (e.g. *cashew*). The aim with most crops is to seek to achieve the optimum crop cover as soon as possible after planting, in order to intercept as much radiation as possible during the lifetime of the crop. The duration of the immature phase varies between crops from, for example, less than a year for *passion fruit* and *papaya* to eight to ten years for *palms* (dependent on tree density). The conversion ratio (or radiation-use efficiency) is expressed in units of g (dry matter) MJ^{-1} (intercepted radiation). Excessively high leaf temperatures and/or dry air (low humidity or large saturation deficit), soil water stress and nutrient stress can all reduce the photosynthetic efficiency. Losses of dry matter as a result of respiration by a large standing biomass (e.g. the trunk of a *palm*) in a warm climate are another reason for apparent low conversion efficiencies.

The aim of plant breeders and others is to maximise the amount of dry matter (or energy) in the plant that is allocated to the useful product. This is known as the harvest index and varies considerably between species. For example Corley (1983) listed the harvest indices (above-ground dry matter) recorded for a selection of a well-managed plantation crops as 0.42 for *oil palm* to 0.30 for *coconut* and 0.20 for *cocoa*. Few attempts have been made to quantify the harvest index for tropical fruit crops, but Corley (1983) cited values of 0.37 for the proportion of dry matter invested in the fruits of *apple* and 0.50 for *citrus*.

Using this analytical approach it is possible to calculate the potential yield of a crop and, by comparing this with the actual yield seek to identify possible reasons for a yield deficit. Corley (1983; 1985) did such an analysis for a similar selection of plantation crops. Water stress can influence each of the growth processes described above, including crop establishment, leaf expansion (light interception), photosynthesis (conversion efficiency), flower formation, pollination, fruit shedding, fruit development, fruit expansion and the harvest index, whilst root extension, depth and distribution affect the amount of water easily available to the crop.

Plant–water relations

Water deficits in plants develop as a consequence of water loss from the leaves as the *stomata* open to allow the ingress of carbon dioxide from the atmosphere for *photosynthesis* and the egress of water vapour (*transpiration*). This is referred to as a *gaseous exchange* process (water vapour for carbon dioxide). Stomata are found on either the adaxial (upper) surface of the leaf or the abaxial (lower) surface, or both.

The water lost by *transpiration* from the leaf mesophyl cells is replaced by water drawn from the soil into the roots, and then up the stems and through the leaves along the *xylem vessels*. Water moves along a gradient of *water potential* from relatively wet soil (high potential) to relatively dry air (low potential). The energy driving this process comes primarily from solar radiation, which is providing the latent heat needed to evaporate water (*transpiration*). The energy status of the water is described in terms of its *water potential*, which in the plant has two principal components, the *osmotic potential* (due to the presence of salts in solution) and the *pressure potential* (or *turgor pressure*). In the soil the principal component is the *matric potential* (a result of the *capillary forces* in the soil pores and the *attraction* of water molecules to soil particles) and, if there are salts in solution, the *osmotic potential*.

A *pressure bomb* is commonly used to measure the *leaf water status* (*leaf water potential* and its components), whilst a *tensiometer* measures the *matric potential* in the soil. A *porometer* (there are several types) measures the *stomatal conductance* (a measure of the degree of stomatal opening). *Infrared gas analysers* are used to measure *photosynthesis* and *instantaneous transpiration* rates (Monteith *et al*., 1981; Squire *et al*., 1981)

Crop water requirements

Actual crop water use (*ET*) can be measured (by means of water balance, sap flow or micro-meteorology) or estimated (by calculation) in a number of ways. The *water balance approach* involves measuring the change in water content (volumetric) of the soil profile (ΔW) over a period of time after allowing for rainfall (P), runoff (R) and deep drainage (D), and finding ET by difference:

$$ET = P - R - D \pm \Delta W$$

This can be done at different scales – from a whole catchment, when comparing changes in land use from, for example, rain forest to *tea* or *oil palm*, to an individual tree grown in a large container (known as a lysimeter). Changes in soil water content can be measured *gravimetrically* or with a *neutron probe* or a *capacitance probe*.

Evapotranspiration (*ET*) has two components: *transpiration* (*T*) and *evaporation* (*E*) from the soil (and crop) surface. Both processes occur simultaneously, and there is no easy way of distinguishing between the two. When the crop is small, water is predominantly lost by evaporation from the soil surface (while it remains wet), but once the crop canopy covers the ground *T* becomes the main process (Allen *et al*., 1998).

The *sap-flow method* (of which there are several variations) involves measuring the rate of flow of water up the stem using a heat pulse (or by carrying out a heat balance for a section of tree trunk). It is well suited to tree crops and has been tried, for example, on *citrus* and *olive*.

Micro-meteorological methods, namely the Bowen-ratio and eddy-covariance methods, involve measuring the flux of water vapour above a crop using an array of sensors. These methods have been used with several of the fruit crops reviewed in this book, including *citrus*, *date palm*, *passion fruit* and *mango*.

In most practical situations, *potential crop evapotranspiration* (ET_c) is estimated using a formula such as the Penman equation or the Penman–Monteith equation, both of which require standard weather data, or a well-sited evaporation pan such as the USWB Class 'A' pan (E_{pan}). These give estimates of evaporation from a standard crop surface, usually taken to be short grass or alfalfa, well supplied with water, now known as *reference crop evapotranspiration* (ET_o) (Allen *et al.*, 1998). To convert this to potential water use by a specific crop (ET_c) a crop factor (K_c) is needed. This varies with the stage of development of the crop.

$$ET_c = K_c \times ET_o$$

A pan factor (K_p), its value depending on the siting of the pan, is needed to convert E_{pan} to ET_o, thus:

$$ET_o = K_p \times E_{pan}$$

Unfortunately, few researchers define precisely the methods they have used to calculate crop water use (there are several versions of the Penman equation). This can sometimes lead to confusion. The guidelines provided by Allen *et al.* (1998) are intended to help to standardise the approaches used internationally. Similarly, in two hard-hitting but valuable papers, Allen *et al.* (2011a; 2011b) highlight the knowledge, skill and awareness needed if large errors are to be avoided when attempting to measure *ET* in the field. The advantages and disadvantages of each method are listed, together with the basic quality standards to be met if the data are to be valid and representative of the surroundings. Allen *et al.* (2011b) also describe the ways in which data should be documented so that readers can judge their authenticity. These two papers should be essential reading for scientists working in this field of study. Many papers would not get published if reviewers insisted on this level of quality control.

Water productivity

There are several ways in which water productivity can be defined, and again it is necessary to be very precise in order to compare like with like. The term *transpiration efficiency* is used to describe dry matter production per unit of transpiration, at short time scales (normally seconds to minutes, up to a day). Alternatively, *water-use efficiency* describes dry matter production per unit of water lost by *evaporation* (from the soil and crop surface) and by *transpiration*. For practical purposes, it is often easier to compare the water-use efficiency on the basis of the *commercial yield* per unit of *evapotranspiration* (evaporation plus transpiration) or per unit of rainfall and/or irrigation. It is important to be able to differentiate between these descriptors when making comparisons; they are rarely defined precisely. *Water productivity* is a generic term covering all these terms (Turner, 1986; Carr and Stephens, 1992).

As an example, for a *citrus* crop yielding 45 t fresh fruit ha^{-1} in an area where the annual evapotranspiration (*ET*) is 1500 mm, of which transpiration is 1050 mm, the *water-use efficiency – ET* (for yield) is 3 kg ha^{-1} mm^{-1} (45000/1500), and the *transpiration efficiency* is 4.3 kg ha^{-1} mm^{-1} (45 000/1050). If the total annual rainfall is 1200 mm, the *water-use efficiency for rain* is 3.8 kg ha^{-1} mm^{-1} (45000/1200). If 300 mm of supplementary irrigation increases yields by 5000 kg ha^{-1}, the incremental *yield response to irrigation* (or irrigation water productivity) is 16.7 kg ha^{-1} mm^{-1} (5000/300). Water productivity values like these are a valuable way of evaluating the effectiveness of various agronomic or drought mitigation practices, or for assessing in crop yield and financial terms, the value of irrigation. They can also act as a benchmark against which to judge good practice.

One simple way of quantifying the yield response to water is that proposed by Doorenbos and Kassam (1979), using the following relationship:

$$(1 - Y_a/Y_m) = K_y(1 - ET_a/ET_m)$$

where Y_a is the actual harvested yield, Y_m is the maximum harvested yield, ET_a is the actual evapotranspiration and ET_m is the maximum evapotranspiration. *Ky* is the slope of the linear relationship (assumed) between the *relative yield decrease* and the *relative evapotranspiration deficit*, known as the '*yield response factor*'. The higher the value of K_y the more sensitive the crop is to water stress.

Based on an analysis of the published results of experiments, Doorenbos and Kassam (1979) developed *yield response functions* for the total growing period for a selection of crops (including the following fruit crops: *banana*, *citrus*, *grape*, *olive* and *pineapple*), and for individual development stages of these crops. The K_y values so obtained were intended to help optimise the planning, design and operation of an irrigation project, taking into account the effect of different water regimes on crop production. It is not known how widely used or successful this approach has been. The K_y values for *banana* were, for example, 1.2–1.35, implying 'high sensitivity' to water stress in both cases. By contrast *pineapple* was classified as having 'low sensitivity'. The target *water-use efficiencies* (irrigation) for *banana* were presented (for the estimated maximum yields at that time) as 3.5–6.0 kg m^{-3} (fruit, 70% water, ratoon crop), and for *pineapple* 5–10 kg fresh fruit m^{-3} for the plant crop and 8–12 kg m^{-3} for the first ratoon (1 ha mm = 10 m^{-3}).

Despite the simplistic use of the yield response factor (K_y), this approach to the development of yield response functions served a purpose at the time. Results of subsequent experiments, however, failed to substantiate the K_y values listed. This was particularly true for perennial fruit crops where there are carry-over effects from year to year, and there are considerable differences in responses to irrigation/drought between cultivars and rootstocks. An alternative approach has recently been published by the FAO for fruit crops and vines (Steduto *et al.*, 2012). It focuses on strategies for developing production functions from published data, and making recommendations for *deficit irrigation* (see below for definition) for a selection of fruit crops that are grown mainly in subtropical and temperate regions (including *avocado*, *citrus* and *olive*), but none from the tropics (Fereres *et al.*, 2012).

These relationships between yield and water all depend on the fundamental link between *dry matter production* (*W*) and *transpiration* (*T*) through the gaseous exchange process:

$$W \alpha e_w (\Sigma T)$$

where e_w is the *transpiration efficiency*. e_w does not have a constant value, but varies with the inverse of the *saturation deficit* of the air (*D*):

$$e_w \alpha 1/D$$

What this means in practice is that the water productivity is always less in situations where the air is dry compared with humid conditions. Irrigation can never completely compensate for rain!

PART III: IRRIGATION SYSTEMS

Successful irrigation depends on being able to apply the right quantity of water at the right time as uniformly as possible across what may be a large area. As the scale of production of orchard crops varies considerably – as well as the topography, soils and the financial resources and skills available – so the methods of irrigation adopted vary. They can broadly be classified into three categories: flood irrigation (Figure 1.18), sprinkler irrigation (Figure 1.19) and trickle (or drip) irrigation (Figure 1.20). In addition there is a composite method known as bubbler irrigation (Figure 1.21).

Figure 1.18 A flood irrigated vineyard in Central Valley, California. Excess water, which can be reused, runs off the end of the furrow – (MKVC).

Figure 1.19 Under-tree mini sprinklers are commonly used in orchards, sometimes on a drag hose as in this example – Israel (MKVC).

Figure 1.20 Drip irrigation allows the precise application of water to (or below) the soil surface through a network of plastic pipes and emitters. In the foreground, the control-unit connects the network to a water source with valves, filtration and fertiliser injection facilities – Swaziland (MKVC).

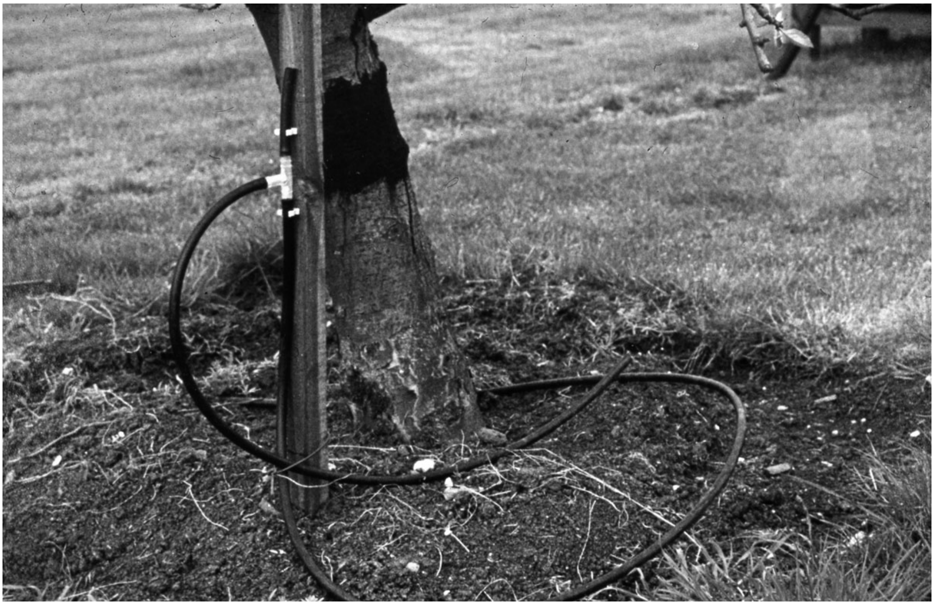

Figure 1.21 Bubbler irrigation was developed for use in orchards in the 1970s. It is a low-pressure system that applies water direct to a basin surrounding each tree at a rate controlled by the differences in the height between the top of the outlet pipe and a reference point – apple orchard, UK (MKVC).

- *Flood irrigation*. This traditional irrigation category includes *furrow* and *basin* irrigation, and also *border strip* (a less common method than the other two). *Furrow irrigation* is commonly used in row crops, including orchards. Careful grading of the soil surface is necessary to obtain relatively uniform distribution of water across a field, with the water discharge rate matched to the slope and length of the furrow and the infiltration rate of the soil. Deep seepage (unseen) and excess runoff can lead to water wastage with the risk of waterlogging and salinity. Furrow irrigation is practised on tree crops including *bananas* (although the ratoon crops develop in different positions from the plant crop). *Basin irrigation* (small, bunded, flat areas surrounding one or more adjacent trees) is suitable for all tree crops, and is ideally suited for irrigating an individual homestead tree.
- *Sprinkler irrigation*. Low pressure *micro-sprinklers* (under-tree) are very popular in orchards. They were introduced in the 1960s, and are suitable for all tree crops; they followed after the introduction of *conventional sprinklers* (these became popular in the 1940s and 1950s). When mounted on high risers, sprinklers can also serve as a method for frost protection (or other types of climate modification, such as humidification, and cooling of fruit to encourage colour formation (anthocyanin), as in *apples* (Figure 1.22)). High-pressure, mobile *rain guns* cover a large land area, but the large droplets can damage the soil and the tree foliage; sprinklers on *drag lines* are ideally suited for orchards; *centre pivots* need enough space and suitable topography to operate effectively, but they can be automated.

Figure 1.22 Sprinkler irrigation can be used as a system of climate modification, including misting, frost protection or, as in this example, to reduce the temperature of fruit to a level that allows the red pigment (anthocyanin) to develop in these Red Delicious apples – USA, (USDA ARS).

- *Drip irrigation*. First introduced to field and orchard crops in the late 1960s and 1970s, this method of irrigation is now very popular in modern orchards (together with micro-sprinklers). It involves the precise application of water to the soil surface through a network of plastic pipes and emitters, which can be above ground or buried (but it can then be difficult to see if there have been any blockages). Drip irrigation has been used successfully with many fruit crops, but it requires very good management to be fully effective.
- *Bubbler irrigation*. This novel method of irrigation was developed in the USA during the 1970s for use in orchards (Rawlins, 1977). Small basins around each tree are fed from a low pressure, buried plastic drainage pipe water delivery system. The rate of application and the amount of water to apply are controlled by the difference in height between the top of the outlet pipe and a fixed, reference position. *Bubbler irrigation* has been used to irrigate *date palm* and *citrus*.

No one system is necessarily better than another. All can be made to work well, given the right situation and good management.

Irrigation scheduling

Irrigation scheduling is the process of deciding when to irrigate and how much water to apply. The objective is to maintain optimum soil water conditions for crop growth in order to meet crop yield and quality targets with minimum water wastage. Although many approaches have been promoted over the years for all crops, it remains the case that only a minority of farmers use an objective (scientific) method of scheduling irrigation, and most still rely solely on their judgment or intuition. The concept of a *soil water deficit* is an important component of irrigation scheduling, virtually independent of the method of scheduling used. It is a measure of how much water is needed to bring the soil profile back to *field capacity* (the maximum depth of water that soil can retain against gravity). A *limiting deficit* is the critical deficit beyond which a crop will begin to suffer water stress. *Deficit irrigation* is when only a proportion of the water needed to rewet the soil to field capacity is applied at each irrigation event. This can sometimes be more economic than full irrigation.

Rising energy, labour and water costs, the need to increase water productivity, less water available for abstraction due to expansion of cropped areas, intensification of existing plantations, increasing competition for limited resources, climate change risks and demands for greater environmental protection are now the driving forces influencing technology choice in irrigated crop production. In this context a good understanding of soil–plant–water relations is important, and more accurate scheduling may prove to be a useful adaptation strategy.

Conclusion

In the following chapters, an attempt is made to interpret the results of research on the water relations and irrigation requirements for individual fruit crops, and to draw useful conclusions from which irrigation practices can be improved and future research prioritised.

As was the case with plantation crops, each chapter follows a similar format. After an introduction, the centre of origin of the crop is described, together with the current centres of production and production trends. There then follows a description of the key crop development stages, including root growth, with an emphasis on how water availability influences each stage. A detailed review of research on fundamental plant–water relations, crop water requirements and water productivity then follows. Where appropriate, irrigation systems suitable for the crop are then considered, together with irrigation scheduling methods. Not all crops have been researched to the same level of detail.

Endnotes

1 *Advances in Irrigation Agronomy: Plantation Crops* (Carr, 2012a).

2 Known as the Azores, South Atlantic, North Pacific, South Pacific and Indian Highs, these high-pressure cells shift towards the Poles in the summer and towards the Equator in the winter.

2 Avocado

Introduction

The avocado is a fruit of Central America and Mexico where it has been a staple dietary component for the indigenous people for at least 9000 years. For the rest of the world it is a relatively new fruit. The centre of diversification is thought to encompass the rainforests of the subtropical to tropical highland areas of Mexico, Guatemala and Honduras, and probably extends to Pacific coastal Costa Rica. This area includes habitats ranging from sea level to altitudes in excess of 3000 m with an associated diversity of climates. This has resulted in genetic diversity and adaptability to warm subtropical areas as well as the tropical highlands and humid tropics (Knight and Campbell, 1999; Whiley *et al.*, 2002).

The first commercial orchards were planted in the early 1900s in California, where much of the pioneering research was undertaken (Figure 2.1). There are now about 25 000 ha grown along the Californian coast and inland about 60 km (Faber, 2006). In Australia, the avocado industry extends from latitude 17º S to 35º S with conditions varying from wet summers and dry springs (east) to hot, dry summers and cool, wet winters (west) (Turner *et al.*, 2001). In semi-arid climates, such as those found in California, Chile, Israel and Australia, irrigation is essential. In other areas, irrigation is supplementary. However in the humid, summer-rainfall subtropics of Florida, Australia and South Africa, and in parts of the humid tropics such as Mexico, Brazil and Indonesia, unirrigated farming systems can be successful. Although national average yields of fresh fruit are low (< 10 t ha^{-1}), good growers in the semi-arid, winter-rainfall subtropics can obtain 12–15 t ha^{-1} and, in the humid, summer-rainfall subtropics, the best can achieve up to 20–25 t ha^{-1}. A target yield of 30 t ha^{-1} from existing genotypes is considered to be realistic (Wolstenholme and Whiley, 1995). In 2009, the principal producing countries were Mexico (with about 30% of the world total of 3 million t), followed by Chile, USA, Indonesia, Dominican Republic, Colombia, Peru, Brazil and China (FAOSTAT, 2011). Avocados are grown as far north as the Black Sea coast (40º N) and as far south as New Zealand (40º S) on a range of soil types (Wolstenholme, 2002; Partridge, 1997).

The avocado is one of the best understood of the subtropical/tropical fruit crops, as illustrated by the comprehensive book edited by Whiley *et al.* (2002), within which the irrigation of avocado is summarised by Lahav and Whiley (2002). Because of its importance internationally, the water relations of the avocado have been the main focus of research, particularly in semi-arid areas.

Crop development

Races

There are three ecological races of avocado that are given varietal status within the species: *Persea americana* var. *drymifolia* (Mexican race), *P. americana* var. *guatemalensis* (Guatemalan race) and *P. americana* var. *americana* (Antillean, West Indian or Lowland race). These differ in their relative cold tolerance, with the Mexican race being the most cold tolerant and the Antillean the least. Inter-racial crossing has taken place to such a degree that the most economically important cultivars in both subtropical and tropical areas are the result of hybridisation between races, for example cv. Fuerte (a Mexican × Guatemalan hybrid originating in Mexico, which for many years led the world in commercial production), and cv. Hass (developed and selected in California, and which has now displaced Fuerte in most places that have a Mediterranean-type climate) (Knight and Campbell, 1999; Knight, 2002). The Mexican and Guatemalan ecotypes are both indigenous to the elevated montane forests or ‘tropical highlands’ where, predominantly, summer and autumn rain is followed by a dry winter and spring, which is when flowering occurs. Both these races, to varying degrees, are also adapted to many warm and cool subtropical areas.

Vegetative growth

The tree is evergreen, (although strictly it is classified as wintergreen because the longevity of the leaves is no more than 12 months and the entire leaf canopy is replaced during the renewal spring growth that comes after flowering), with a monopodial trunk up to 20 m tall. All the branches are also monopodial and therefore indeterminate, ending in a vegetative bud. Shoot growth in mature trees is synchronised into flushes of varying vigour, duration and extent. This synchronous growth pattern is marked during the quiescent period by shorter internodes and a ring of closely spaced buds. Leaves expand to full size in about 30 days, and last for 10–12 months (Scora *et al.*, 2002).

The avocado tree has a vegetative bias, resulting in a preferential allocation of assimilates to shoot growth rather than to reproductive organs. This bias, coupled with the relatively short life of the leaves (for a subtropical fruit tree species) results in the rapid production of leaves and increased shading within the canopy, which reduces the number of well-lit terminal shoots capable of flowering. However, except in the spring when shoot growth is synchronised by flowering, not all of a tree flushes at the same time. As a result, much of the canopy remains well lit. Young leaves are sinks for photoassimilates for about their first 40 days (Schaffer and Whiley, 2003).

The sensitivity of tree growth to water availability was illustrated in one of the first irrigation experiments with avocado, undertaken in California by Richards *et al.* (1962). Wind damage prevented fruit yields from being recorded, but tree growth (trunk diameter) increased (over the six years of the experiment, 1956 to 1961) faster the more frequently the soil was irrigated (the quantity of water applied probably also varied). Tensiometers and resistance blocks were used to schedule irrigation in order to maintain soil water potentials in the three treatments above −0.05 (wettest), −0.1 and −1.0 MPa (driest) at depths of 0.30 m. There was a cumulative increase in the diameter of the trunk over time.

Flowering

In subtropical areas, flower initiation occurs during the autumn, when shoot growth enters a long quiescent phase. Flowering occurs during late winter and spring with anthesis spread over a three to eight week period (Whiley and Shaffer, 1994). Inflorescences are panicles of cymes (strictly determinate thyres with branches terminating in flowers). The inflorescence can either be functionally determinate (where the terminal vegetative bud aborts) or functionally indeterminate (where the bud grows and competes with the developing fruits) (Scora *et al.*, 2002; Figure 2.2).

Avocados are protogynous (a flower in which the stigma is receptive before the pollen is shed from the anthers of the same flower) and exhibit synchronous dichogamy (anthers and stigmas mature at different times), in which flowers open on the first day when the pistil is receptive, and then close and open again on the second day when the pollen is shed and the pistil is no longer receptive. Cultivars vary in the time of opening and closing of the flowers (Purseglove, 1968). Cool conditions during anthesis can influence the periodicity of this process, affecting the

Figure 2.1 An avocado grove in the coast hills of Central California (EF). See also colour plates section.

Figure 2.2 Avocado inflorescence. Flower initiation occurs in the autumn with flowering in late winter and spring – Zimbabwe (MKVC).

need or otherwise for cross pollination (achieved by interplanting cultivars which differ in the timing of the opening and closing of the flowers).

A large heavily flowering tree may have one to two million flowers, but produce up to 200–300 fruits only (Figures 2.2 and 2.3). During flowering, as some of the floral parts have stomata (see below), the canopy surface area available for water loss is increased by an estimated 90% (Whiley *et al.*, 1988).

Fruiting

Under favourable conditions more fruit are set than the trees can support. In subtropical climates fruit load adjustment is characterised by shedding during the first three to four weeks after fruit set and again in early summer (Schaffer and Whiley, 2002).

The fruit is botanically a berry with a thick, fleshy mesocarp surrounding a single large seed (Figure 2.4). It is renowned for its nutritive value. The oil is used by the pharmaceutical industry. The avocado is unusual in that cell division continues, albeit at a slower rate, for as long as the fruit remains on the tree. Differences in fruit size appear to result from cell number as well as cell size. Sound fruits will not ripen while held on the tree (Scora *et al.*, 2002). Water deficits during critical stages of fruit ontogeny have been linked to fruit disorders such as ring-neck, in which corky lesions develop at the

Figure 2.3 Avocado tree in flower, Sri Lanka. A large, heavily flowering tree may have over a million flowers, but produce only 200–300 fruits (HDT).

abscission sites on the fruit stalk, elongated fruits (cv. Hass) and reductions in the internal fruit quality (Schaffer and Whiley, 2002).

Immediately after flowering, many fruits drop from the tree. This is one of the most critical periods, determining both yield and fruit size. There is competition for resources between developing fruit and new shoot growth at a time when net assimilation rates and root growth are depressed. In warm, humid subtropical climates, assimilates from current photosynthesis, as opposed to stored sources, are critical for fruit retention and growth (Whiley *et al.*, 1995).

In a series of container experiments in Australia, Turner *et al.* (2001) found that reproductive growth was very resistant to water deficits. Young fruit continued to grow, whilst vegetative growth was reduced. Watering only half the root system maintained vegetative and reproductive growth up to fruit set, but drying the root zone wholly or partially for several months caused fruit drop (cv. Hass) (Neuhaus *et al.*, 2007). The avocado is not considered to be drought tolerant (Whiley and Shaffer, 1994).

Figure 2.4 Avocado fruits: under favourable conditions more fruits are set than the tree can support – Papua New Guinea (HDT). See also colour plates section.

Roots

The root systems of avocado trees were described by Colt (1940) in California as being relatively shallow, with fine fibrous rootlets in greatest abundance at or near the surface of the soil. These roots were thought to function best when protected by moist, undisturbed leaf mulch, as in their native or wild habitat in the forests of Central America. Subsequently there have been several attempts to quantify some of these observations.

Depth and distribution

The roots of mature trees (cv. Fuerte) were excavated at two (irrigated with basins) sites in Mexico by Salazar-Garcia and Cortés-Flores (1986). On the sandy loam soil (alt. 1800 m) roots reached depths of 1.4 m, with 43% of all the roots by dry mass in the top 0.2 m and 65% in the top 0.6 m. The horizontal spread was 3 m. By contrast, on the clay soil (alt. 1300 m), the maximum depth of rooting was about 1.2 m, with 21% in the surface 0.2 m and 83% in the top 0.6 m. The horizontal spread was up to 2.5 m. The total dry mass of roots was nearly four times greater in the sandy loam soil than in the clay.

In South Africa, Durand and Claassens (1987) excavated roots of 18-year-old trees (irrigated) to depths of 1.1 m (the limit of measurement) and as far as 6 m laterally from the trunk. Root distribution (by dry mass) varied with the health of the tree (some were affected by root rot), but in healthy trees it was fairly uniform vertically and horizontally. They cited other observations of roots being relatively evenly distributed to depths of 1.2 and 2.1 m in deep uniform soils, with some roots even reaching 3.3 m, but with the main concentration being in the top 1.5 m.

Salgado and Toro (1995) originally summarised the results of a detailed study in central Chile of the changes over time in the spatial distribution of ‘active’ roots (white, ≤ 2 mm in diameter) of mature trees (cv. Hass grafted on to Mexicola seeding rootstocks, 12 years old), as influenced by the method of irrigation (drip and micro-sprinkler) on two soil types (clay loam and sandy loam). Subsequently, Salgado and Cautin (2008) reported the experiment in full. The density of roots, as observed on trench walls (0.75 m deep × 3.0 m wide) in the autumn was twice that observed at other times of the year under drip irrigation and three times that with micro-sprinklers. The roots were mainly found in the surface layers (0–0.25 m). Of secondary importance was the observation that there were 25% more roots in the clay loam soil compared with the sandy loam, and 30% more roots under drip irrigation than micro-sprinklers. Both of these observations were influenced by the large number of roots present in the fine soil-drip irrigation combination. Overall, the highest root frequency was within 1 m from the trunk.

In a comparison of two levels of drip irrigation in Israel, Cantuarias *et al.* (1995) observed roots on the sides of an excavated trench in May and June (the period of maximum root activity). Analysis of root distribution with depth from the soil surface indicated that 69% (single drip line) and 80% (five drip lines) of the total root number (in a 1.0 m deep profile) were concentrated in the top 0.36 m.

Neuhaus *et al.* (2009) summarised the results of observations of the root systems of 15-year-old trees (cv. Hass on Guatemalan seedling rootstocks), in which irrigation had been withheld for six months. On a sandy soil in Western Australia, there was no effect on root length density down to 1.3 m from the soil surface. However, the extended drying reduced the length of roots adjacent to the soil surface from 2.1 ± 1.5 m m^{-2} to 0.8 ± 0.4 m m^{-2}.

Root extension

In Florida, Ploetz *et al.* (1993) measured rates of extension of shoots and roots (recorded in a rhizotron) over one year for two cultivars (Simmonds and Lula, both grafted onto Waldin seedling rootstocks). Peaks of shoot and root growth occurred in alternating flushes on 30- to 60-day cycles. Although shoot extension ceased during late autumn and winter, root extension continued throughout the year.

Summary: crop development

1. There is considerable genetic diversity within the species and adaptability to warm subtropical areas as well as to the tropical highlands and humid tropics.
2. The tree is evergreen, with a monopodal trunk up to 20 m tall. Shoot growth is synchronised into flushes. Leaves are relatively short lived.
3. Tree growth is very sensitive to water availability.
4. Flower initiation occurs in the autumn, with flowering in late winter and spring.
5. Since flowers form on the terminal ends of branches, avocado trees need to expand each year in order to remain productive.
6. A large heavily flowering tree may have over a million flowers, but produce only 200–300 fruits.
7. Fruit load adjustment is characterised by shedding during the first three to four weeks after fruit set and again in early summer.
8. Differences in fruit size appear to result from cell number as well as cell size.
9. Water deficits during critical stages of fruit ontogeny have been linked to fruit disorders such as ring-neck.
10. Reproductive growth is very resistant to water deficits (compared with vegetative growth).
11. Avocado trees are conventionally considered to be shallow rooted, although roots extend to depths greater than 1.5 m (even down to 3.3 m), and laterally up to 3 m (even 6 m).
12. The majority of white unsuberised feeder roots are found in the top 0.60 m of soil. They grow into the decomposing litter layer. Avocado roots have few or no root hairs.
13. Peaks of shoot and root growth occur in alternating flushes.
14. Although shoot extension ceases during late autumn and winter, root extension can continue throughout the year, with an autumn peak.

Plant–water relations

Stomata

In a detailed study using a scanning electron microscope and porometry, Blanke and Lovatt (1993) examined the structure and functions of the inflorescences of cvs. Hass and Fuerte. Whiley *et al.* (1988) had previously undertaken a similar study. Leaves develop a waxy cuticle on both surfaces. Before this waxy layer is formed, the young leaves, and the sepals and petals, are densely pubescent, creating an effective boundary layer. Stomata occur on the abaxial surface of the leaves (350–510 mm^{-2}) and are also present on the abaxial surfaces of the sepals and petals at low densities (*c.* 3 mm^{-2}) and on young fruit (50–75 mm^{-2}). The fruits are covered by a waxy film on the surface of the exocarp, which is interrupted by stomata when young, but these become plugged and less active with age. The floral stomata appeared to be functional, whereas 80% of the stomata found on old leaves were closed. As a result, the transpiration rate per unit area of sepal/petal exceeded that from leaves, whilst transpiration from young fruits exceeded both. Since, during flowering, there are up to two million transpiring flowers with an estimated surface area of 54 m^2 in the periphery of the tree (Blanke and Lovatt, 1993) their contribution to the total water use of a tree is considerable, around 13% according to Whiley *et al*. (1988). These features, together with physiological adjustment in response to soil and atmospheric water deficit (stomatal conductance declines with increases in the saturation deficit of the air (Schaffer and Whiley, 2002)), contribute to the adaptability of avocado to climates as diverse as humid and semi-arid (Scora *et al*., 2002).

In Mexico, Barrientos Priego and Sanchez Colin (1987) compared the stomatal densities of a selection of cultivars with different growth habits, which included dwarf mutants. There was nearly a fourfold difference in densities (units not specified) between the extremes, with the trend of increasing stomatal density with reductions in tree height. Stomatal density in cultivar Fuerte, included as a standard, was intermediate.

In a series of experiments in Australia, designed to answer fundamental questions about the physiology of the avocado and linking that to yield and water productivity, Turner *et al*. (2001) found (surprisingly) that water deficits caused the stomata to close (and transpiration to cease) before any other changes, including leaf and young fruit expansion, were detected. Diurnal fluctuations in fruit diameter are proportionally greater in young fruit (Schaffer and Whiley, 2002). Citing others, particularly Neuhaus (2003), Schaffer and Whiley (2003) stated that stomatal conductance is a more reliable early indicator of a water deficit in avocados than measurements of leaf water content, leaf water potential or growth variables. Stomatal conductance begins to decline when the leaf water potential falls below -0.4 MPa, and continues to decline until it reaches -1.0 to -1.2 MPa, when the stomata are fully closed. This decline is accompanied by a parallel reduction in net photosynthesis.

From a series of (not very convincing) field measurements of plant water status made in Israel on an irrigated crop (cv. Hass), Sharon (1999) and Sharon *et al*. (2001) confirmed the sensitivity of trunk and leaf contractions to diurnal changes in leaf water potential (diurnal range -0.15 to -1.05 MPa). They also showed how the stomata remained open during the day (even at 36 ºC). The capacity of avocado trees to maintain fast rates of transpiration was attributed to a high root hydraulic conductivity (compared with *Citrus* spp.).

Photosynthesis

Being an understorey highland rainforest species, the avocado is shade tolerant and has an adaptive advantage in colonising small gaps when the forest canopy is disturbed (Schaffer and Whiley, 2002). Light saturation of mature leaves of field-grown trees (cv. Hass) occurs at a photon flux density (PPF) of 1100 μmol m^{-2} s^{-1}. This is about half the PPF in full sun at midday at low to mid latitudes.

In a detailed, well-reported study, Chartzoulakis *et al*. (2002) compared the responses of two cultivars (Fuerte and Hass) to a moderate water deficit over a six-month period.

Avocado plants, two years old, were grown in pots outdoors in Crete (Greece). Water-deficit-induced changes in leaf anatomy were observed in both cultivars. These included reductions in the thickness of (most of) the histological components of the mesophyll. The resultant 35–45% reduction in leaf porosity restricted rates of carbon dioxide (CO_2) diffusion to the chloroplasts within the leaf, and lowered the internal CO_2 concentrations. Water deficits also resulted in concurrent reductions in stomatal conductance. As a result of both these water-deficit-induced processes, photosynthesis rates were reduced. Drought also reduced the osmotic potential, mainly as a result of dehydration (rather than through active solute accumulation) and, in particular, increased tissue elasticity in both cultivars. By so doing the pressure potential (turgor pressure) was maintained. Growth data suggested that cv. Hass was more productive than cv. Fuerte under well-watered conditions, but was more susceptible to water deficits.

Transpiration

Under conditions of high evaporative demand (ET_o = 7–15 mm d^{-1}) in the northern Negev, Israel, actual transpiration (T, based on sap flow measurements) on trees well supplied with water reached a maximum of only 3 mm d^{-1}. The ratio T/ET_o was low and remained in the range 0.13–0.21. For irrigated, 14-year-old avocado trees (cv. Ettinger), leaf water potentials stayed relatively constant (*c.* −0.5 MPa for sunlit leaves). The same experiment showed that enlargement of the wetted soil volume from 25% to 75% improved tree water status and transpiration rates, as well as root growth (Cantuarias *et al.*, 1995).

Xylem vessels

Differences exist between the races and genotypes in the susceptibility of the xylem vessels to cavitation when under water stress. In a comparison of relative vulnerability (to cavitation), Reyes-Santamaría *et al.* (2002) found that the three avocado races had higher vessel frequencies (20–22 vessels mm^{-2}) than the two cultivars (Fuerte and Hass, *c.* 12 vessels mm^{-2}), but smaller vessel diameters (races 99–107 μm; cultivars 116–117 μm). In terms of the vulnerability index (= vessel diameter/frequency) the two cultivars had the highest values, whilst the races had the lowest. It was concluded that the races were less susceptible to hydraulic failure than the cultivars and that within the races the Guatemalan was better adapted to water deficits than the Mexican or Antillean races. A dwarf genotype had characteristics intermediate between the three races and the two cultivars.

The choice of an appropriate rootstock is important, not only for optimising tree growth and productivity, but also for reducing water consumption. In a glasshouse experiment in California, Fassio *et al.* (2009) related sap flow rates to the xylem anatomy of two clones (Duke 7 and Toro Canyon) and two composites (Hass scion grafted on to Duke 7 and Toro Canyon rootstocks). Duke 7 had a 29% higher flow rate (transpiration) than Toro Canyon, whether or not it was grafted. There were no differences in the xylem vessel features in the stems of any of the cultivars. However, the roots of Duke 7 had wider and fewer vessels than Toro Canyon, as well as a 19% larger total vessel area, suggesting that the differences in water consumption of Hass on different rootstocks may be linked to differences in the efficiency of the conductive tissue in the root.

In Australia, the xylem vessels of droughted avocado plants were observed to contain tyloses (outgrowths into the xylem lumen). Even 84 days after re-watering, up to 34% of the vessels remained occluded by tyloses. Fluorescent dyes showed that these restricted water flow in the stems as a result of a 50% reduction in hydraulic conductivity. Restrictions to water flow in the leaf petiole were caused by embolisms/cavitation. In well-watered trees, or those subjected to drought on only one side of the trunk, no tyloses were found in the xylem vessels (Turner *et al*., 2001; Neuhaus *et al*. 2007).

Summary: plant–water relations

1. Young leaves (and the sepals and petals) are densely pubescent, creating an effective boundary layer.
2. Leaves develop a waxy cuticle on both surfaces, which is interrupted by stomata on the abaxial surface (350–510 mm^{-2}), many of which are blocked.
3. Stomata are also present on the sepals and petals at low densities (and on young fruit).
4. During flowering, the canopy surface area available for water loss is considerably increased.
5. Stomatal closure is an early indicator of water stress.
6. The avocado tree is shade tolerant.
7. Water deficits induce changes in leaf anatomy resulting in a reduction in leaf porosity, which restricts CO_2 diffusion.
8. Even when the potential evapotranspiration (ET_o) rates were large (7–15 mm d^{-1}), the maximum rate of transpiration measured was only 3 mm d^{-1}. The ratio T/ET_o was always small (0.13–0.21).
9. Leaf water potentials remained constant (−0.5 MPa) over the same range of ET_o values.
10. Differences exist between the races and genotypes in the susceptibility of the xylem vessels to cavitation when under water stress.
11. Differences in water use by cv. Hass on different rootstocks may be linked to the conductivity of the rootstock.
12. Droughted plants develop tyloses in the xylem vessels, which restrict water flow in the stem.

Crop water requirements

In subtropical South Africa, Hoffman and du Plessis (1999) attempted to quantify the water use of six- to seven-year-old trees (cvs. Fuerte and Hass) grown in a deep red clayey soil. They based their assessment on the depth of irrigation water applied (micro-sprinklers) to re-wet the soil back to field capacity (as determined from tensiometers), and on the rainfall falling on the ‘wetted’ area (assumed to be 70% effective). In the summer, water use peaked at 5 mm d^{-1} for cv. Fuerte and 4 mm d^{-1} for cv. Hass. In the winter, the corresponding values were 1.5–2.0 mm d^{-1} and below 1.5 mm d^{-1}. The annual totals were 1020 mm and 890 mm, respectively.

In Western Galilee, Israel, on a heavy soil, water uptake occurred at a maximum depth of 1.2 m, but with 95% of the water coming from the top 0.60 m. By contrast, in the Northern Coastal Plain of Israel, water uptake occurred at depths down to 1.8 m with a smaller proportion (80%) coming from the 0–0.60 m layer (Shalhavet *et al.*, 1979). Rates of evapotranspiration (ET_c) were relatively constant throughout the irrigation season (June to October) at 3.0–3.5 mm d^{-1}. The ratio ET_c to E_{pan} (USWB Class A) increased over this period from 0.42 (June) to 0.61 (October). The irrigated trees were aged between five and eleven years old, and spaced 6 m × 6 m apart.

In Mediterranean-type climates, the mid-summer water application rates recommended for young trees are as follows: year 1, 4–8 L d^{-1} $tree^{-1}$; year 2, 8–15 L d^{-1} $tree^{-1}$; year 3, 30–50 L d^{-1} $tree^{-1}$ and year 4, 80–150 L d^{-1} $tree^{-1}$(Lahav and Whiley, 2002). At a tree density of 278 trees ha^{-1}, the figures for year 4 equate to 2.2–4.2 mm d^{-1}.

In California, growers apply annually between 450 and 1500 mm of irrigation water depending on the location, less in the north and more in the south. This is in years with typical rainfall totals between 250 and 500 mm. For mature trees the recommended crop coefficient $K_c = 0.7$ together with a +10% leaching factor, dependent on water quality. Local differences in topography and exposure can be important, for example: ET_o values on different sides of a hill varied considerably: in the winter there was a 120% difference between the bottom, middle and top of a hill, and a 32% difference in the summer (Faber, 2006).

Summary: crop water requirements

1. There have only been a few attempts to measure the actual water use of avocado trees.
2. In Mediterranean-type climates, peak rates of water use (in summer) appear to be between 3 and 5 mm d^{-1}.
3. There are apparent differences in rates of water use between cv. Hass and cv. Fuerte.
4. Water uptake has been recorded at a depth of 1.8 m.
5. For mature trees, the crop coefficient ($K_c = ET_c/ET_o$) is usually within the range 0.4–0.6.
6. There is no published evidence to show that when a tree is flowering its water requirements increase (although this is commonly stated).

Water productivity

Sufficient water is needed during the flowering period to ensure adequate fruit set, and during the period of rapid fruit growth to maximise fruit size and to minimise fruit drop. In Mediterranean climates, there is a risk of adverse effects of reduced aeration and soil cooling if excess water is applied during the spring. The need for irrigation is reduced in the autumn and is (usually) unnecessary in the winter (when there is usually enough rain) (Lahav and Kamar, 1983; Lahav and Whiley, 2002).

Following the experiment in California described above (Richards *et al.*, 1962), one of the earliest irrigation experiments reported was undertaken in the northern coastal plain in Israel over a six-year period (1968–1974). Beginning in the fifth year after planting, four irrigation intervals (7, 14, 21 and 28 d) were compared, although this comparison was confounded by differences in the quantities of water applied (mean annual totals 889, 745, 668 and 594 mm respectively). The soil was a vertisol, with more than 60% clay down to 1.5 m. The aim was to wet the soil profile back to field capacity at each irrigation, to depths of 0.90 m (the 7 and 14 d treatments) and 1.20 m (the 21 and 28 day treatments). Treatments were imposed from early June to the end of October. Vegetative growth (trunk diameter, tree height and volume) was reduced as the irrigation interval increased. The build-up of salts was greatest under the extended interval treatments, although these were leached by winter rain (Kalmar and Lahav, 1977).

Interpreting treatment effects on yields is complicated by the tendency of avocado trees to yield well only in alternate years. The cultivar Hass is particularly prone to ‘alternate bearing’, which in the experiment summarised above was triggered by frequent irrigation. When averaged over all six years, yields of fresh fruit from each of the four irrigation interval treatments were similar for cvs. Ettinger (average *c.* 47 kg tree^{-1}) and Fuerte (40 kg tree^{-1}). But in the case of cv. Hass there was a 10 kg tree^{-1} yield advantage in favour of irrigation at weekly intervals compared with every 28 days (63 compared with 53 kg tree^{-1}). Frequent irrigation increased individual fruit weight, particularly with cvs. Ettinger (+ 35 g or 11%) and Hass (+18 g or 9%). Irrigation began too late to influence fruit set, but there was a small increase in oil content from frequent irrigation. It was concluded that a 21 d irrigation interval was the most appropriate, since it reduced tree size without loss of fruit yield (Lahav and Kamar, 1977).

A similar experiment was conducted by Kurtz *et al.* (1992) over the period 1984–1988 on the coastal plain of Israel. The responses of three cultivars were compared (Ettinger, Fuerte and Hass), all grafted on to Antillean seedling rootstocks, to three levels of water application. These were 70%, 100% and 130% of the annual amount recommended in Israel for mature trees (700 mm), after adjusting the value of K_c for tree size (trees were planted in 1980). The soil was a silty loam, evaporation was measured in a USWB class A pan (April to November total *c.* 1300 mm), and water was applied through one micro-sprinkler per tree, with the rates adjusted so that there was a uniform wetted area of 20 m^2 per tree. For two of the cultivars (the exception being Hass), tree vegetative growth increased with the amount of water applied, such that cv. Ettinger needed additional pruning. For various reasons, fruit yields varied considerably from year to year, but when totalled over the five years the only significant effects were the 32% yield advantage of the 130% treatment over the 100% (and 70%) treatments, for cv. Ettinger (47 t ha^{-1} cf. 35 t ha^{-1}), and a corresponding 15% benefit for cv. Fuerte (40 t ha^{-1} cf. 32 t ha^{-1}). Over five years, assuming linearity, these represent yield responses to irrigation of 1.1 and 0.7 kg m^{-3} respectively. Salinity levels in the soil were greatest with the low water applications.

A not very convincing water-production function was developed from the results of irrigation experiments conducted on the coastal plain of Israel over a number of years with the same three cultivars (Ettinger, Fuerte and Hass). This suggested that, based on relative yields, a seasonal (summer) water application of 650 mm (in addition to winter rainfall totals of 500–600 mm) was needed to obtain an 'optimum' yield (defined as 0.91 times the maximum). Between seasonal water applications of 300 to 600 mm the yield response in absolute terms was 15.7 ± 3 kg ha^{-1} mm^{-1} (1.57 kg m^{-3}) of fresh fruit (Steinhardt, 1991). Assuming a linear response, this equates to a yield of 10 t ha^{-1} for an application of 650 mm water.

Another experiment in Israel compared four levels of water application (60, 80, 100 and 120% of the 'commonly applied amount', as determined with tensiometers and a neutron probe). Variable nitrogen levels were confounded with the water treatments, which were applied through a drip irrigation system to a clay soil. Tree girths (cvs. Fuerte and Hass) over the seven years of the experiment increased with the annual average depth of irrigation water applied (range 283 to 572 mm, in addition to winter rainfall). Similarly, yields of fruit increased at 2.2 kg m^{-3} (cv. Hass) and 1.6 kg m^{-3} (cv. Fuerte) (Lahav *et al*., 1992). The results of this and several other irrigation experiments in Israel were subsequently re-evaluated and confirmed by Lahav and Aycicegi-Lowengart (2006).

The sensitivity of avocado to water deficits was illustrated by the results of an experiment in the Jordan Valley, Israel (32º42′ N 36º35′ E; alt. −204 m) in which the responses of avocado trees (cv. Hass) grown in lysimeters to three irrigation frequencies and two soil volumes (100 L and 200 L) were described by Silber *et al.* (2011; 2012). Pulsed irrigation, in which water was applied for 10–20 minutes every 30 minutes throughout the day, was compared with a treatment in which water was applied daily from the night to the morning, and a third treatment in which the same quantity of water was applied every alternate day (all through a drip system). Over the three years the experiment lasted, vegetative growth was greatest in the 200 L soil volume at all irrigation frequencies. Differences between irrigation treatments were only statistically significant in the two years when fruit were harvested in the low volume (100 L) soil treatment, when pulsed irrigation outperformed night-time irrigation, which in turn outperformed the alternate day treatment. There were no treatment effects on flowering intensity or fruit set, but fruit drop was greater in the 100 L soil volume treatment than in the 200 L one, and greatest in the alternate day irrigation treatment and least in the pulsed treatment. The authors invoked limitations in carbohydrate supply as being the most likely cause of fruitlet abscission, although no data were presented to support this hypothesis,

The interim results of an irrigation experiment in California were reported by Faber *et al.* (1995). In an area close to the coast with winter rainfall (average c. 400 mm), it was not until the fourth year of treatments (consisting of seven different levels of replenishment, from 0.37 to 1.11 ET_o) that there was a difference between treatments in cumulative yields (there was no control 'rainfall only' treatment), reaching nearly 800 kg tree^{-1}. In contrast, tree size in general again increased with the amount of water applied, so that yield per unit of canopy volume declined. At the start of the experiment, the trees (cv. Hass) were six years old and had previously been irrigated. The loam soil was deep (> 2 m). A single micro-sprinkler was used to apply water to each tree at weekly intervals. At this location, in years with adequate rainfall, irrigation is only probably needed for a two- to three-month period from mid-July.

In a field experiment on a sandy soil in Western Australia (31° S 115′ E), Neuhaus *et al.* (2009) studied the effect of drying the root zone beneath half or all the canopy on water productivity. The treatments were imposed for eight months from February (after fruit drop) through to maturity in September (cv. Hass on Guatemalan seedling rootstocks, 15 years old). In the following season, normal irrigation practices were restored. In both treatments yields were reduced proportionally more than the reduction in water supply, when compared with the well-watered control treatment, whilst re-watering did not restore yields in the following season. Contrary to expectations, water productivity was therefore reduced. The main impact of a reduced water supply was fruit abscission linked to dry soil around the roots rather than to the water status of the leaves or fruits, which was maintained. There was no apparent adverse effect of drying half the root system on fruit quality. Again, contrary to expectations, there was no evidence to support the concept of ‘root signals’ influencing leaf conductance and vegetative growth, although there was no explanation for the large fruit drop in the partially irrigated treatment (Neuhaus *et al.*, 2009). Electrical signalling was, however, identified by Gil *et al.* (2008) in Chile as a possible mechanism to explain the fast response of stomata of avocado to changes in soil water status, since root-to-leaf abscisic acid transport alone did not explain the process.

Excess water

The avocado is sensitive to flooding and poor soil aeration, resulting from inadequate or slow drainage, soil compaction, excess rain and/or poor irrigation management leading to high water tables (see Schaffer, 2006, for a detailed review of the topic). This can be a serious problem everywhere. Unlike some other species (e.g. mango), avocado does not possess any anatomical or morphological adaptations in response to low soil oxygen levels. For grafted trees like avocado, flooding sensitivity is primarily due to the rootstock and not to the scion, and attempts are now being made to identify/select for flood-tolerant rootstocks, for example in Chile (Fassio, *et al.*, 2011) and in South Africa (Farrow *et al.*, 2011). Root rot (*Phytophthora cinnamoni*) is associated with wet soils, and it was originally thought that damage to avocado trees from wet soil was due to increased destruction of roots by the causal organism. It has since been shown that soil flooding and the resultant hypoxia (reduction in oxygen level) or anoxia (complete lack of oxygen) can damage roots, even in the absence of *P. cinnamoni* (Schaffer, 2006). One of the earliest detectable changes is a decline in gas exchange (net CO_2 assimilation and transpiration) as a result of stomatal closure. Visible symptoms include wilting, leaf abscission and root necrosis. The effects of oxygen deficiency on fruit yields have not been well quantified. In flood-prone areas of southern Florida, commercial growers are advised to plant avocado trees on raised beds, 0.9 m high by 0.9–1.5 m wide (Schaffer, 2006). Research needs to be focused on how the root systems respond to waterlogging.

Salinity

Among fruit trees, avocado is the most salinity-sensitive crop, but the races differ in their relative sensitivity. Rootstocks and seedlings of Mexican race cultivars are considered to be the most sensitive to saline conditions, and those of the Antillean race the most tolerant. Chloride toxicity is the major contributing factor, aggravated by sodium. The advice given to growers in Israel is that the chloride content of water used to irrigate avocado should not exceed 120–150 mg L^{-1} for Mexican rootstocks and 200–250 mg L^{-1} for Antillean rootstocks (Schaffer and Whiley, 2002; Wolstenholme, 2002). Examples of some of the research on salinity are presented below.

Several long-term experiments have been carried out to quantify the yield responses to salinity of avocado and to specify critical levels that should not be exceeded. For example, Lahav *et al.* (1992) reported the preliminary results of a salinity experiment in Israel in which the responses of two rootstocks to four levels of salinity (chloride) in the irrigation water were compared. There were two levels of irrigation, 85% and 115% of the recommended amount (applied with micro-jets). The chloride concentrations in the leaves were three times higher in the trees grafted (cvs. Ettinger and Hass) on Mexican rootstocks than in those on Antillean rootstocks. Increases in the chloride content of the water from 90 to 380 mg L^{-1} reduced the cross-sectional area of the trunk. Tree growth was faster at all levels of salinity in the treatment where excess water was applied. Fruit yields over the four to five years of records responded in a similar way, declining by 25% on average over the same range of salinity levels.

Later, Shalhevet (1999) summarised the complete set of results from the same experiment for the period 1984 to 1994 (although the stated chloride levels cited were slightly different, namely 80 to 400 mg L^{-1}). The mean salinity level of the soil solution was about 1.8 times that of the irrigation water, and increasing the quantity of water applied did not result in substantial leaching during the irrigation season. Rather, winter rainfall leached the accumulated salts. As expected, trees grafted on Mexican rootstocks showed greater sensitivity to salinity than those on Antillean rootstocks. For those on Mexican rootstocks average yields (for both scions) declined from about 40 kg tree^{-1} to 15 kg tree^{-1} over the range of chloride levels tested (the trees were five to eight years old).

A second example of salinity research is the long-term (six years) experiment in California described by Oster *et al.* (2007), in which the effects on fruit yield (cv. Hass on Mexican seedling rootstock) of the amount of saline irrigation water applied (0.9, 1.1 and 1.3 ET_c were targeted) and the frequency of application (one, two or seven times a week) were assessed. In the introduction to their paper, the researchers also succinctly summarised previous research on this topic. The average electrical conductivity and chloride concentration of the water, corrected for rainfall, were 0.7 dS m^{-1} and 1.8 mmol L^{-1}, respectively. Trees irrigated seven times a week yielded less than those irrigated less frequently. During the last two years of the experiment, when yields no longer increased with the age of the tree, yields of the two less frequently irrigated treatments both increased with the amount of water applied. This was because the soil water salinity level had not reached a critical level of about 4 dS m^{-1}, when water uptake by the roots is restricted. The critical or threshold electrical conductivity value, beyond which yields declined due to toxicity, was estimated to be 0.57 dS m^{-1} (a very low value compared with other crops). The rate of decline in relative yield was then linear, with a slope of -0.63 per unit of salinity. The authors concluded that, for this cultivar and rootstock, the average annual salinity of the irrigation water, after allowing for the dilution effect of rain, should not exceed 0.6 dS m^{-1} for maximum yields.

As growers rely increasingly on saline water for irrigation, so does the need to identify cultivars with improved salinity tolerance, which can be incorporated into a breeding programme (Crowley, 2004). In California, several rootstocks, some of which were selected in Israel, have been shown to have a greater capacity to exclude chloride and sodium. The relative sensitivity of root growth to salinity compared with shoot growth was demonstrated in an experiment in which avocado seedlings were grown in nutrient solution. As a result, Bernstein *et al.* (2004) recommended that root growth should be considered as an important criterion for judging the tolerance of rootstocks to salinity.

Summary: water productivity

1. There is very little reliable evidence on the water productivity of avocado.
2. This is due in part to the difficulty of undertaking long-term irrigation experiments on a tree crop that bears fruit in alternate years.
3. Although quantitative data are lacking, it is commonly stated that ‘sufficient water’ is required during flowering to ensure ‘adequate’ fruit set, and during the period of rapid fruit growth to ‘maximise’ fruit size and to ‘minimise’ fruit drop.
4. Examples of yield improvements are limited as there is rarely an unirrigated ‘control’ treatment for comparison, or insufficient information is given in the paper to enable water productivity to be calculated.
5. The best estimate of water productivity (based on relatively low fruit yields, *c*. 9–10 t ha^{-1}) is between 1 and 2 kg m^{-3}.
6. Although the cultivars responded differently, an early recommendation in Israel was to irrigate every 21 d, since tree size was reduced without loss of fruit yield.
7. Soil flooding and the resultant reduction in oxygen level can damage roots even in the absence of root rot. The effects on fruit yields have yet to be quantified.
8. Avocado is particularly sensitive to salinity, notably chloride ions. Rootstocks vary in their sensitivity. The Mexican race is the least tolerant and the Antillean the most.

Irrigation systems

Drip irrigation of avocado trees began on hillsides in San Diego County, California during the 1970s. Hillsides offered natural protection from frosts, the land was cheaper than elsewhere, and there was less risk of urban encroachment (Figure 2.5). Other

Figure 2.5 Avocado and Citrus orchards in southern California. On this undulating land, trickle irrigation is widely practised. Note the windmills for frost protection – (MKVC).

factors that favoured drip irrigation included the high cost of water, salinity and opportunities to automate the system (Gustafson, 1979).

In California, young trees are irrigated with one dripper or a modified micro-sprinkler (with a cap that can be removed later as the trees grow). Most growers convert to micro-sprinklers, or remove the cap, in the second or third year after planting to wet a larger area. Only a few older orchards still use high-pressure, solid-set sprinkler systems (Faber, 2006).

At Malaga in the south of Spain, Olalla *et al*. (1992) compared drip irrigation at four levels of application (three drippers per tree, with $K_c = 0.44, 0.57, 0.66$, and five drippers per tree, $K_c = 0.57$) with micro-sprinklers at two frequencies (two- and three-day irrigation intervals, $K_c = 0.50$ and 0.46). Evaporation was estimated from a USWB Class A pan. The average annual depth of water applied, through a fully automated system, to each treatment over the three years the experiment ran, ranged between 674 mm (drip, $K_c = 0.44$) to 1024 mm (five drippers, $K_c = 0.57$). Because of direct evaporation losses from wet soil, the larger the proportion of wetted soil surface the greater the water application necessary, particularly with micro-sprinklers. Although there were differences in vegetative growth, fruit yields were similar (cv. Hass, five to seven years old). In an unconvincing report, the principal conclusion was that, when estimating how much water to apply to a coarse textured soil, K_c should be no less than 0.55.

Flood irrigation should be avoided where there is a risk of hypoxia or anoxia (Lahav and Whiley, 2002). Irrigation is used for frost protection in susceptible areas such as Florida, either by means of micro-sprinklers (to release heat from the soil by conductance to protect the lower limbs of the tree) or over-tree sprinklers (release of latent heat as the water freezes).

Irrigation scheduling

In a review of the literature on irrigation scheduling, du Plessis (1991) strongly recommended the use of tensiometers in commercial avocado orchards. The critical matric potentials, below which the soil should not be allowed to dry, at depths of 0.30 m, were −30 kPa for sandy soils and −50 kPa on clayey soils. The review emphasised that water deficits during flowering, fruit set and early fruit growth should be avoided and that over-irrigation should be avoided at all cost, because of the risk of soil oxygen deficiency and root rot. Tensiometers (installed in pairs at depths of 0.30 and 0.60 m) are also recommended in California (Anon., 2011), in order to refine the decision about when to start irrigating and to check that excess water is not being applied. Careful and representative siting of these instruments is essential if reliable data are to be collected. But, as Faber (2006) noted, ‘there are quite a few growers who do go out and read their tensiometers on a regular basis and schedule irrigations based on those readings. There are also a lot of rusted tensiometers out in the fields where growers gave up using them.’

Plant-based scheduling methods have also been proposed. For example, Turner *et al.* (2001) compared the use of stomatal conductance measurements to schedule irrigation (at 25% of full conductance, an arbitrary number) with the water-balance method based on a Class A pan (water applied = 1.2 E_{pan}, which kept the stomata open, except during hot weather). Over a season, scheduling by stomatal conductance reduced the water applied by one third; it also reduced leaf gas exchange and the number of fruits on the trees relative to the water-balance method. Because of its complexity, stomatal conductance measurement was not a recommended scheduling method for commercial use. In Israel, Winer and Zachs (2007) have proposed a plant-based method of scheduling for avocado, based on daily measurements of changes in the diameter of the tree trunk.

In order to improve water productivity and to minimise pollution, Kiggundu *et al.* (2012) evaluated several combined irrigation scheduling and nutrient management practices in southern Florida (25° 20′ N 80° 20′ W; alt. 4 m). The amount of leaching, and the productivity and nutrient status of young avocados (cv. Simmonds; irrigated with micro-sprinklers from planting) were monitored in a four-year study. Basing the irrigation timing on the soil water status reduced the volume of water applied by 87%, and the quantity of phosphorus leached by 74%, compared with irrigating to a set schedule (twice a week for two hours, this being local practice). Tensiometers, installed at depths of 0.15 and 0.20 m were programmed to switch on the irrigation when the soil water potential reached −0.15 kPa. The water saving was even better when irrigation was scheduled using the conventional soil water-balance approach (when $ET_c = K_c \times ET_o$). Fruit yields were, however, below those obtained from the soil water-based treatments with the corresponding fertiliser inputs. Water productivities ranged from less than 1 kg fresh fruit per m^3 of water applied (set schedule) up to 12 kg m^{-3} (water balance): the overall average irrigation water productivity was about 7 kg m^{-3}. These figures are considerably greater than those quoted above. Experiments of the type described here are notoriously difficult to do well, as it is impossible to avoid confounding more than one variable in order to compare like with like.

Water conservation

Some water-management issues that have emerged as politically important include the following:

The avocado industry in Australia is committed to improving water productivity, with a vision of doubling irrigation efficiency (however that is defined) by 2020. This is despite the fact that the industry is a relatively small consumer of water on a national scale ($<1\%$). Irrigation water use varies considerably across the principal areas where avocados are grown, from 300–500 mm in the high rainfall areas in northern Queensland to 800–1800 mm in areas further south and in parts of Western Australia (Anon., 2006). In this context, Aleemulah *et al.* (2001) studied irrigation practices on four avocado farms over two years (2000 and 2001) in Queensland. Using capacitance probes to monitor water use, and recording how much water was applied and when, they attempted to establish benchmarks by which to judge good irrigation practice. Irrigation water productivities varied from a low of 50 trays of fruit per million litres to a high of 532 trays per million litres. Assuming each Australian tray contains 6 kg of fruit, these equate to 0.3 kg m^{-3} and 3.2 kg m^{-3} respectively, a tenfold difference. This gives an idea of what it is possible to achieve in practice.

Similarly, new water-quality regulations are being imposed in California. No contaminants in water are allowed to leave a grower's land (this often occurs with winter rainfall), including sediments. Growers are expected to monitor water quality themselves (Faber, 2006).

Increasingly, producers will be judged, by governments, supermarkets and consumers, on water management criteria such as these.

For areas where there are restrictions on the availability of water for irrigation, a number of water-conservation strategies have been identified by Witney and Bender (1992). Although these strategies were intended for growers in California facing mandatory reductions in water availability, some have general application and include the following:

- Use a science-based irrigation scheduling method (such as tensiometers or capacitance probes).
- Do not irrigate diseased or damaged trees.
- Cut back/stump trees that have attained 100% canopy cover to a height of 1.2–1.8 m, whitewash immediately to prevent sunburn, and allow the trees to re-grow. Stump in alternate 1 ha blocks; irrigation frequency can then be reduced.
- Thin crowded orchards by removing alternate trees before they have achieved full canopy cover, but when the trees have already grown into each other. Sprinklers next to thinned trees can be capped.
- Mulch young trees: keep them weed-free.

Mulching

The benefits that can be obtained from mulching go beyond water conservation. These were demonstrated by Wolstenholme *et al.* (1998) in South Africa. In an experiment lasting three years the application of 150 mm depth of composted pine bark to six-year-old trees (cv. Hass on Duke 7 rootstocks) increased the average annual yields over the following three years by 23% (from 20.0 to 24.4 t ha^{-1}). This period included two good cropping years either side of one 'off' year. The yield benefit followed an average 7% increase in fruit size (and more export-quality fruit) and a 15% increase in fruit number. This response was not just due to water conservation, since the trees were irrigated (drip). Feeder roots proliferated in the pine bark mulch, which supplemented a natural mulch of leaf litter. Stress levels were reduced (e.g. leaf temperatures were up to 6 ºC cooler), there was less pedicel ring-neck and seed coat degeneration was delayed. With a half-life of five years, the commercial application of this mulch, although expensive, was considered to be financially viable, and it was recommended that mulching should become a standard crop-management practice. Careful choice of the mulching material is necessary, and Whiley (2002) has listed some of the materials used in Australia. These include barley and sorghum straw, sugar cane tops and groundnut husks. Fire and frost are possible hazards associated with mulching.

Summary: irrigation systems

1. Both drip and under-tree micro-sprinklers have been/are successfully used to irrigate avocado trees.
2. Basin irrigation is not recommended.
3. The proportion of the root zone that it is necessary to keep wet has not been clearly established.
4. The value of the crop coefficient depends on the method of irrigation, and the frequency and degree of wetting the soil surface, but, for mature trees, a value of about 0.6 is reasonable.
5. Tensiometers (and capacitance probes) are recommended for scheduling purposes: the soil should not be allowed to dry, at depths of 0.30 m, below soil matric potentials of −30 kPa on sandy soils, and −50 kPa on clayey soils.
6. Plant-based indicators of when to irrigate may be worth considering.
7. Mulching of young trees is a recommended water conservation measure and has other benefits.
8. External pressures to encourage growers to use water effectively and wisely will increase.

Conclusions

Although, globally, avocado production is dominated by Mexico and other tropical countries, most of the research summarised here has been done in subtropical regions, notably Australia, California, Israel and South Africa. Unfortunately, much of the research reviewed in this chapter was poorly reported, and the data sometimes difficult to interpret. Of 60 references cited on avocados, only a quarter were in refereed journals, whilst half had been published in 'the grey literature', as proceedings of conferences or yearbooks, sometimes with limited quality control. The remainder were chapters in books, and in one excellent book in particular (Whiley *et al.*, 2002), and extension leaflets. In part, the emphasis on conference proceedings is understandable, given the active support given to research by grower associations in a number of countries and the need for stakeholders to be kept informed. The long-term nature of irrigation research on tree crops in particular, and its cost, makes it imperative that the (often incomplete) results of research are communicated regularly to the industry. Sometimes this is at the expense of publishing in peer-reviewed papers, the science on which recommendations to growers are based. Getting the balance right is not easy.

Despite avocado's importance as an irrigated crop, and the diverse environments in which it is grown, there have only been a few attempts to measure its actual water use, and to quantify water productivity in systematic ways. Much of the research is empirical and lacks generic application. There has been only a limited amount of fundamental research on the water relations of avocado to assist in the extrapolation of results from one location to another. As growers rely increasingly on saline water for irrigation so there is an increasing need to continue to identify cultivars with improved salinity tolerance. There is great variability in responses to water (and salinity) due to year-to-year variability, site-to-site differences, rootstock and scion interactions, and cultural practices, such as plant population. This makes research on avocadoes particularly challenging!

Summary

The results of research on the water relations and irrigation needs of avocado are collated and reviewed in an attempt to link fundamental studies on crop physiology to irrigation practices. Background information is given on the centre of origin (Mexico and Central America) and the three distinct ecological areas where avocadoes are grown commercially: (1) cool, semi-arid climates with winter-dominant rainfall (e.g. southern California, Chile, Israel); (2) humid, subtropical climates with summer-dominant rainfall (e.g. eastern Australia, Mexico, South Africa) and (3) tropical or semi-tropical climates, also with summer-dominant rainfall (e.g. Brazil, Florida and Indonesia). Most of the research reported has been done in Australia, California, Israel and South Africa. There are three ecological races that are given varietal status within the species: *Persea americana* var. *drymifolia* (Mexican race); *P. americana* var. *guatemalensis* (Guatemalan race) and *P. americana* var. *americana* (Antillean, West Indian or Lowland race). Inter-racial crossing has taken place. The effects of water deficits on the development processes of the crop are summarised, followed by reviews of plant–water relations, crop water requirements, water productivity and irrigation systems. Shoot growth in mature trees is synchronised into flushes. Flower initiation occurs in the autumn, with flowering in late winter and spring. Flowers form on the ends of the branches. A large, heavily flowering tree may have over a million flowers, but only produce 200–300 fruits (Figure 2.6). Fruit-load adjustment occurs by shedding during

Figure 2.6 Avocado fruit (cv. Hass), botanically a berry, is rich in vitamin D and, to a lesser extent, vitamins C and B. This variety was developed and selected in California – Tanzania (TCEC). See also colour plates section.

the first three to four weeks after fruit set and again in early summer. Water deficits during critical stages of fruit ontogeny have been linked to fruit disorders such as ring-neck. Reproductive growth is very resistant to water stress (compared with vegetative growth). Avocado is conventionally considered to be shallow rooted, although roots extend to depths greater than 1.5 m. The majority of feeder roots are found in the top 0.60 m of soil and root extension can continue throughout the year. Leaves develop a waxy cuticle on both surfaces, which is interrupted by stomata on the abaxial surface (350–510 mm^{-2}), many of which are blocked by wax. Stomata are also present on the sepals and petals at low densities (and on young fruit). During flowering, the canopy surface area available for water loss is considerably increased. Stomatal closure is an early indicator of water stress, which together with associated changes in leaf anatomy, restricts CO_2 diffusion. There have only been a few attempts to measure the actual water use of avocado trees. In Mediterranean-type climates, peak rates of water use (in summer) appear to be between 3 and 5 mm d^{-1}. For mature trees, the crop coefficient (K_c) is usually within the range 0.4–0.6. The best estimate of water productivity is between 1 and 2 kg fruit m^{-3}. Soil flooding and the resultant reduction in oxygen level can damage roots, even in the absence of root rot. Avocado is particularly sensitive to salinity, notably that caused by chloride ions. Rootstocks vary in their sensitivity. Both drip and under-tree micro-sprinklers have been/are successfully used to irrigate avocado trees. Mulching of young trees is a recommended water-conservation measure and has other benefits. A large proportion of the research reviewed has been published in the 'grey literature' as conference papers and annual reports. Sometimes this is at the expense of reporting the science on which the recommendations are based in peer-reviewed journals. The pressures on irrigators to improve water productivity are considered.

3 Cashew

Introduction

Cashew (*Anacardium occidentale* L.) is grown principally for its nutritious kernel, the edible part of the nut[1] (Figure 3.1). The hard shell surrounding the kernel is a source of 'cashew shell nut oil', which can be used in a number of polymer-based industrial processes. The swollen pedicel (the stalk to a single flower), known as the 'cashew apple', is another potentially valuable by-product, for example as a fresh fruit and source of juice (especially in South America), since it is very high in vitamin C, and as a basis for alcohol production.

Cashew is a native of South America with a likely centre of origin in the *cerrados*[2] of central Brazil, or possibly in the coastal zones of north-eastern Brazil, since this is where there is the greatest diversity of the *Anacardium* species. Cashew was probably introduced into Africa and India by the Portuguese in the sixteenth century. It is now found throughout the tropics at latitudes between 27° N (Florida) and 28° S (southern Africa) at altitudes below about 800 m. Cashew is a crop generally associated with coastal regions (Nambiar, 1977; Martin *et al*., 1997; Bezerra *et al*., 2007; Nair, 2009; all citing others).

Vietnam is currently (2010) the world's largest producer of cashew with an annual production of 'nut-in-shell' of 1.16 million t (from 340 000 ha), followed by India (613 000 t; 923 000 ha) and Nigeria (594 000 t; 330 000 ha). Brazil is the largest producer in South America (102 000 t; 750 000 ha). Cashew is also an important crop in eastern Africa, for example in Mozambique and Tanzania. The total world production is 3.59 million t from 4.0 million ha (FAOSTAT, 2012). Some of these data appear to be totally unrealistic, including the world average yield of nearly one tonne per hectare, and should be viewed with caution. The complexity of the farming systems within which cashew may be an important component makes it difficult to collate reliable statistics (Ascenso, 1986a).

The structure of the cashew industry in the principal producing countries has been described by Hall *et al*. (2007). For example, in Vietnam, where the industry has expanded rapidly in recent years (it now produces 32% of the world's crop), the majority of cashew growers are typically smallholders with 2-ha orchards. Similarly, in Tanzania most households have fewer than 100 cashew trees (Martin *et al*., 1997). By contrast, in Brazil, although small- and medium-size producers are in the majority (in 1995/96 there were 195 000 farmers growing cashew trees), 32% of the crop is

Figure 3.1 Cashew is grown principally for its nutritious kernel, the edible part of the nut – China (MKVC). See also colour plates section.

produced on large-scale land holdings (>100 ha) (Hall *et al.*, 2007). In India, where cashew is described as a 'poor man's crop but a rich man's food', the cashew industry employs around one million people as labourers, mainly women, to process the raw cashew (Nair, 2009).

The water relations of cashew have been the focus of only a limited amount of research, undertaken mainly in Brazil and Australia. This is despite its importance nationally and internationally. It is estimated that less than 1% of the planted area in the world is irrigated, since cashew has the reputation of being a drought-tolerant crop. Irrigation is, however, being encouraged in some regions, for example in north-eastern Brazil (Bezerra *et al.*, 2007). It should be noted that this refers to irrigation of 'dwarf' cultivars grown primarily for cashew apple production.

This chapter begins with a description of the stages of development of cashew (including roots) in relation to water availability, followed by reviews of plant–water relations, crop water requirements, water productivity and, finally, irrigation systems.

With a focus on India, Nair (2009) reviewed in detail the history and role of cashew as a commercial crop, and its future prospects. Bezerra *et al.* (2007) have reviewed aspects of the ecophysiology of cashew with an emphasis on the effects of salinity and nutrient stress on gas exchange and growth processes of seedlings and young plants. In the expectation that a cashew industry would develop in tropical Australia, Grundon (1999) wrote a report reviewing the Australian (and other) literature on cashew.

Crop development

The following topics are considered in this section: vegetative growth, flowering, fruiting, plant density, roots and the partitioning of dry matter.

Vegetative growth

There are two types of cashew, known simply as ‘talls’ and ‘dwarfs’. Both are evergreen trees. ‘Talls’ can grow to a height of more than 10 m and have a domed-shaped canopy with a span of up to 20 m. ‘Dwarfs’ are generally small and low-spreading and require pruning to keep the branches off the ground (Figures 3.2 and 3.3). Dwarf cultivars are less common than ‘talls’, but they are of increasing commercial importance (Ascenso, 1986b; Bezerra *et al*., 2007). Until the 1980s, cashew was propagated by seed, but now grafting of clones on to seedling rootstocks is the accepted method. Cashew comes into production in about the third year after planting.

In its native habitat, the cashew tree has a period of rapid vegetative growth followed by a quiescent stage and then a series of pre-floral vegetative flushes. Flowering and fruit development and maturation follow. The major period of vegetative growth coincides with the rainy season, and the flowering and fruiting phases with the dry season (Grundon, 1999).

Under cultivation, the number and duration of each phase varies depending on local conditions. As an example, the sequence of the crop development stages that occur in Binh Phoc province in Vietnam, where there is a single rainy season, is summarised.

Figure 3.2 A young cashew tree – Malaysia (HDT). See also colour plates section.

Figure 3.3 ‘Dwarf’ cashew trees are generally small and low-spreading and require pruning to keep the branches off the ground – Malawi (HDT).

In the case of young cashew trees, vegetative growth occurs in a series of flushes throughout the year. With mature trees, two to three periods of active shoot growth can be identified. The first flush occurs in late April to May, after the harvest has ended, and soon after the start of the rains. This is followed by a second flush in August or early September. A so-called pre-flowering flush occurs in late October and November, at the start of the dry season (Peng *et al.*, 2008).

Flowering

Flowers, in the form of loose panicles, are produced in the dry season on the ends of branches. Flowers on the same terminal inflorescence can be either male or hermaphrodite (Figure 3.4). Flowering is profuse, with up to 1600 flowers per panicle. The proportion of male flowers varies considerably, depending in part on the cultivar. Pollination is mainly by flying insects (Nambiar, 1977; Nambiar *et al.*, 1990; Grundon, 1999). When well supplied with water (and nutrients) cashew trees can continue to flower throughout the year (although excess rainfall can prevent nut set), but the actual duration of flowering depends on location. For example, in south-eastern Vietnam, flowering and fruit-setting last about two and half months from December to February. Since this is the dry season, irrigation is recommended at this time – see below – (Peng *et al.*, 2008). In tropical Australia, flowering continues over a four-month period coinciding with the dry season (Grundon, 1999).

Water availability can also influence the relative numbers of male and hermaphrodite flowers produced. For example, in an irrigation experiment in the Northern Territory of

Figure 3.4 Cashew flowers are produced in the dry season on the ends of branches. Flowers on the same terminal inflorescence can be either male or hermaphrodite Flowering is profuse, with up to 1600 flowers on each panicle (HDT).

Australia the irrigated treatment had more male flowers per panicle, in weeks three to seven of the flowering phase, than the unirrigated control treatment (Schaper *et al*., 1996).

Fruiting

The development of a nut takes about two months from pollination. In the case of south-eastern Vietnam, harvesting extends over a period of 10–12 weeks, from mid-February to the end of the dry season in April. In the absence of pest and disease problems, poor fruit set and a high rate of premature fruit abscission can limit nut yield for reasons not yet fully understood, but competition for water, nutrients/assimilates may play a major role.

Silva *et al*. (2004) provided an example of the yields that can be achieved when water is not a limiting factor. In north-east Brazil (03° 41′S 35° 43′W), there are two well-defined seasons, a rainy season (the mean annual rainfall is 1640 mm) and a dry season that lasts from April to December. Following field planting in 1990, a selection of early-dwarf cashew clones were compared in terms of fruit and pedicel (cashew apple) yield over six years (1990/91–1995/96). Initially the tree spacing was 6 m × 3 m (555 trees ha^{-1}) but, because there was mutual shading by the end of the third year, the plant density was then reduced to 278 trees ha^{-1}. The trees were drip irrigated daily during the dry season with varying quantities of water, depending on the year/stage of crop development. It was a sandy soil. Large yields were already being harvested in the second year. Over five seasons (1991/92 to 1995/96) the average number of nut-in-shell (and pedicels) harvested annually was around 250 000 ha^{-1}; yields of nut-in-shell were about 1600 kg ha^{-1} (sun or oven dried), and of pedicels close to 17 000 kg ha^{-1} (fresh weight, mostly water). For comparison, the average yield of nut-in-shell in Brazil (from mainly unselected 'talls') is only 140 kg ha^{-1} and in Vietnam 340 kg ha^{-1} (FAOSTAT, 2012). In India, by the year 2000, average yields had reached 865 kg ha^{-1} (Nair, 2009). These figures appear to be realistic.

Plant density

The optimum spacing varies with the age of the tree and its vigour, and with the availability of soil water. Since yields (per tree and per unit area) decline once overlapping of the adjacent canopies occurs (Northwood and Tsakiris, 1967), recommendations for the optimum spacing of these wide-spreading trees vary as they age. There has to be a compromise between high initial yields at a close spacing (e.g. 6 × 6 m; 278 trees ha^{-1}) and larger yields later in the life of the orchard at a wide spacing (up to 15 × 15 m; 44 trees ha^{-1}). In most locations in Tanzania, for example, the recommended spacing is 12 × 12 m (59 trees ha^{-1}) as this allows intercropping in the early years. Where trees grow vigorously, 15 × 15 m is the preferred density. Although high-density planting (e.g. 9 × 9 m) followed by thinning may be appropriate for intensive cultivation, it is not considered to be suitable for smallholders. The associated intercrops vary with location and in Tanzania, for example, include cassava, groundnuts, pigeon peas and pineapples. Mixed cropping (e.g. with citrus) is also practised (Martin *et al.*, 1997). In India, the recommended tree spacing is 7.5 × 7.5 m (178 trees ha^{-1}) or 8 × 8 m (156 ha^{-1}), although high density planting (4 × 4 m; 625 ha^{-1}), followed after 11 years by thinning to 312 ha^{-1} is being evaluated (Nair, 2009).

Using assumptions that are still valid, Dagg and Tapley (1967) showed with a simple water-balance model why a mature crop grown at a close spacing (6 × 6 m) at a location in southern Tanzania (single rainy season, six-month dry season) yielded little. (In this example, it is difficult to disaggregate the effects of water stress and canopy overlapping, since cashew is a peripheral bearing tree and where canopies touch there is no yield). Under closed canopy conditions, severe water stress developed very early in the dry season. By contrast, wide-spaced, clean-weeded isolated trees had access to enough water to transpire freely throughout the year to yield well. The long-term average annual rainfall at the site was 900 mm and the total open water evaporation (E_o) was 2000 mm. The model was sensitive to the ratio of the lateral spread of roots to that of the canopy. Field observation suggested that this ratio was 2:1, and that roots reached a depth of at least 3 m. In this situation, an isolated tree can exploit approximately four times the volume of soil that lies directly beneath the canopy.

Roots

The root systems of cashew trees of different ages in Tanzania were excavated and illustrated by Tsaikiris and Northwood (1967). In a loam to loamy sand topsoil overlying about 3 m of sandy clay subsoil, roots of 30-, 42- and 54-month-old trees extended to depths of 2, >2.3 and >5 m, respectively The spread of lateral roots 18, 30, 42 and 72 months after planting was 1.2, 4.6, 5.6 and 7.3 m from the main stem respectively. This implies that the root systems of 30-month-old trees will interlace with the roots of neighbouring trees when planted at 6 m spacing and meet at 9 m intervals. Similarly, the roots of 72-month-old trees will meet at a spacing of 15 m and interlace at 12 m. Canopy measurements suggested that the lateral spread of roots is about twice that of the canopy. The spreading rooting habit of cashew is a critical factor in the successful adaptation of the tree to semi-arid regions/a dry environment (Dagg and Tapley, 1967).

In his overview report on cashew research in Australia, Grundon (1999) summarised the results of work on roots undertaken by N.K. Richards in the Northern Territory, by J.A. Sherrard and others in Western Australia and north Queensland and by P.J. O'Farrell in Queensland. This was research that had previously been described mainly in unpublished workshop papers. On sandy red earth soils cashew extracted water from depths of at least 1.8 m, whereas elsewhere on a flood-irrigated clay soil the maximum depth of water extraction was 0.8 m, within a 2.7 m distance from the tree trunk. Again in Australia, the soil water content continually declined down to depths of at least 4.0 m in a deep, sandy soil, suggesting root activity at these depths (Schaper *et al.*, 1996).

Partitioning of dry matter

In northern Australia, Richards (1993), cited by Grundon (1999), monitored the dry matter production of a whole cashew tree over a period of 64 months (from 6 months after planting to 70 months). At each harvest, the above-ground dry matter represented more than 75% of the total dry mass, with the roots below ground representing less than 20%. When nut-in-shell and cashew apple were present on the tree, they together represented less than 10% of the total above-ground dry mass of the tree. At 70 months, stems and branches made up 50% and leaves 19% of the total dry mass. A similar distribution pattern was reported from India for eight-year-old trees by Reddy and Reddy (1987): roots 23%, stems and branches 61%, leaves 16%. Presumably in this example no fruits were present.

From his data Richards (1993) developed a model with which to estimate above-ground dry matter production (Y, kg) based on multiple step-wise regression:

$$Y = 44.9 + 18.9A + 2.11C - 88.5H$$

where A (m^2) is a measure of the area of the silhouette of the leaf canopy (based on photographs of the canopy taken from two directions), C is the circumference (cm) of the stem and H is the height above ground of the canopy (m).

Summary: crop development

1. Vegetative growth occurs in two or three identifiable flushes each year.
2. Flowers form on the end of branches in the dry season: they can be male or hermaphrodite.

3. Flowering continues over a two- to four-month period.
4. The development of the nut takes about two months from pollination.
5. Harvesting extends over 10–12 weeks, preferably when it is dry.
6. Wide tree spacing allows intercropping in the early years: close spacing requires surplus trees to be thinned subsequently in order to minimise water stress.
7. The spreading root habit of cashew is critical in its successful adaptation to dry conditions.
8. Roots can extend to depths >5 m: water extraction has been monitored down to 4 m.
9. Nut-in-shell and cashew apple together make up less than 10% of the above-ground dry mass of the tree.

Plant–water relations

Research on gas exchange and the water relations of cashew is limited, but useful work has been reported from Brazil and, surprisingly perhaps, Australia, where cashew is still described as an ‘emerging crop’.

Photosynthesis

In Brazil (22º 54′ S 47º 05′ W; alt. 674 m), De Souza *et al.* (2005) studied factors influencing the photosynthetic process of young (45–55-day-old) dwarf cashew plants (clone CP06) under controlled environmental conditions. Maximum CO_2 assimilation rates were about 13 μmol m^{-2} s^{-1}, with light saturation occurring at a photon flux density of around 1000 μmol m^{-2} s^{-1}. Maximum CO_2 assimilation rates were observed over a broad temperature range of 25–35 ºC, and even at 40 ºC the photosynthesis rate was still close to 50% of its maximum value. Stomatal conductance increased with temperature over the range 20–35 ºC, before declining at higher temperatures. These observations were made at a constant saturation deficit of the air (1.0 kPa, leaf-to-air). Increases in the dryness of the air (from 1.0 to 3.5 kPa) had little effect on CO_2 assimilation rates. This was despite progressive closure of the stomata at saturation deficits greater than 1.5 kPa. Transpiration rates declined over the saturation deficit range 1.0–2.0 kPa, but transpiration then remained constant as the saturation deficit increased to 3.5 kPa. Under natural (open air) conditions, stomatal conductances were high early in the morning, but then declined during most of the rest of the day. Transpiration peaked at around 1400–1500 h. There was evidence of photoinhibition of photosynthesis at high irradiance levels. Collectively these observations were believed to demonstrate the adaptation of cashew to dry environments (De Souza *et al.*, 2005).

Further north in Brazil, (3º26′ S 39º08′ W; alt. 31 m), Lima *et al.* (2010) monitored gas exchange at monthly intervals over a year on leaves exposed to the sun or shaded in a field experiment with mature, dwarf trees. Surprisingly, there were no differences between the irrigated and rain-fed trees in stomatal conductance, transpiration, photosynthesis, internal or external CO_2 concentrations, or leaf temperature. There were, however, differences between sun-exposed and shaded leaves, as well as seasonal variability. Both clones (CCP 76 and BRS 189) tested responded in similar ways. Amorin *et al.* (2011) subsequently reported the results of related gas exchange and other measurements made in a similar experiment, again in Brazil (4º 10′ S 38º 27′ W: alt. 60 m). These included the recording of soluble carbohydrate, potassium, sodium and chloride ion concentrations. Over the five months of measurement (covering the dry season, total rainfall 17 mm), there was seasonal variation, but once again there were no differences (except for photosynthesis) between the two watering treatments. The only exception was that foliar *N*-amino solutes and proline were higher in plants grown under rain-fed conditions than in those that were irrigated. Given the short-term nature of the experiment, it is perhaps not surprising that the yield of nuts from these two treatments were similar. It is not very clear what these two experiments tell us about the physiology of cashew, except the relative insensitivity of gas exchange to dry conditions.

In northern Australia (12º 25′ S 130º 52′ E), light saturation on mature cashew leaves (cv. BLA-273–1) occurred at a photon flux density of about 1200 μmol m^{-2} s^{-1}. Leaves reached full size 25 days after emergence and about 24 days later maximum rates of photosynthesis occurred, remaining high for a further three weeks before declining. The leaf chlorophyll content began to decline about 46 weeks after leaf emergence, signifying the start of leaf senescence. The longevity of a leaf was about one year. As a result of the rapid succession of vegetative growth flushes, leaves on trees in an orchard became shaded within less than six months from emergence, and hence their contribution of assimilates to other growth processes then declined. Only in a dry season did the rate of vegetative growth slow, and then leaves of the flush associated with the development of the panicle probably became the main contributors of carbohydrates to the developing fruits (Schaper and Chacko, 1993).

Subsequently, Schaper *et al.* (1996) monitored leaf gas exchange in three-year-old cashew trees (cv. BLA 39–4) in a field irrigation experiment in northern Australia. Differences in rates of photosynthesis and transpiration on cloudless days between irrigated and unirrigated trees only became apparent after flowering, three or four months after the end of the rainy season. These differences were associated with concurrent reductions in stomatal conductance and occurred in months when the air was dry (saturation deficits of at least 3 kPa). There were no differences between treatments in the chlorophyll content of the leaves until after flowering had ended, when it declined in the leaves of unirrigated trees. Leaf water potentials recorded between 0930 h and 1030 h remained relatively constant at -1.2 MPa in non-irrigated trees, but declined to -1.5 to -1.6 MPa in irrigated trees. This observation highlights the role of the stomata in maintaining the leaf water status of cashew in dry conditions.

Transpiration

The effectiveness of the stomata in controlling water use in cashew was confirmed in a container-grown experiment in Australia (Blaikie and Chacko, 1998). This experiment also demonstrated the potential usefulness of Granier's sap flow system for measuring transpiration in cashew. Reductions in transpiration and photosynthesis as the soil dried were associated with a decline in stomatal conductance. After re-watering, sap flow and leaf gas exchange returned to high levels within three or four days. By contrast, chlorophyll fluorescence measurements were less responsive to soil drying and wetting.

Subsequently, again using the Granier method to measure transpiration by individual five-year-old trees (cv. BLA 273), Blaikie *et al.* (2001) recorded sap flows between 20 and 25 L d^{-1} $tree^{-1}$ (when evaporation rates from a USWB Class A pan were about 4 mm d^{-1}), regardless of the irrigation treatment. Differences between irrigation treatments became clearer, despite large tree-to-tree variability, later in the season when evaporation rates had reached 9 mm d^{-1}. Depending on the treatment, sap flow rates were then within the range 22 to 28 L d^{-1} $tree^{-1}$. When cumulative evaporation following an irrigation event exceeded 30 mm, sap flow rates began to decline relative to those for well-watered trees, falling to 15–20 L d^{-1} $tree^{-1}$. Since the trees were spaced 6 × 8 m (208 trees ha^{-1}), these figures have the following equivalences: 25 L d^{-1} $tree^{-1}$ $\equiv$ 5 m^3 ha^{-1} d^{-1}; 20 L d^{-1} $tree^{-1}$ $\equiv$ 4 m^3 ha^{-1} d^{-1}; 15 L d^{-1} $tree^{-1}$ $\equiv$ 3 m^3 ha^{-1} d^{-1}. By comparison, growers in the same area were applying 500 L $week^{-1}$ $tree^{-1}$ (14 m^3 ha^{-1} d^{-1}) at that time during the May to November dry season.

In a comparison of five mature tree crops in Brazil, stomatal conductances and instantaneous transpiration rates in cashew were similar to those recorded for guava and rubber, but during the dry season were substantially greater than either coffee or guarana (*Paullinia cupana*, a large woody climber). In the rains the differences between the species were less distinct (Sena *et al.*, 2007).

Summary: plant–water relations

1. Light saturation occurs at a photon flux density of about 1000–1200 μmol m^{-2} s^{-1}.
2. In a controlled environment, maximum CO_2 assimilation occurs over the temperature range 25–35 °C.
3. Progressive closure of the stomata occurs at saturation deficits of the air >1.5 kPa.
4. Increases in the dryness of the air (up to 3.5 kPa) do not appear to influence rates of CO_2 assimilation.
5. In the field, differences in rates of photosynthesis and transpiration between irrigated and unirrigated trees only became apparent after flowering, three or four months after the end of the rainy season.
6. These differences were associated with concurrent reductions in stomatal conductance and occurred in months when the air was dry (saturation deficits of at least 3 kPa)
7. Leaf water potentials recorded between 0930 h and 1030 h remained relatively constant at −1.2 MPa in non-irrigated trees, but declined to −1.5 to −1.6 MPa in irrigated trees.
8. Stomata play an important role in maintaining a favourable leaf water status of cashew in dry conditions.
9. Sap flow rates (= transpiration) in the range 20–28 L d^{-1} $tree^{-1}$ (for 200 trees ha^{-1} this equals 4–5.6 m^3 ha^{-1}) have been recorded for well-watered mature cashew trees.

Crop water requirements

No method for estimating (or measuring) the water requirements of cashew under orchard conditions appears to have been proposed or evaluated. The FAO Irrigation and Drainage Papers do not list cashew or specify any of the key variables such as the crop coefficients (K_c) with which to calculate potential evapotranspiration (ET_c) for cashew. The only serious field studies reported are those that used the sap flow methods to measure transpiration of individual trees, with variable results, and with no attempt to scale-up to an orchard size.

Water productivity

Field-scale cashew irrigation experiments have been reported from Brazil and Australia.

Brazil

The results of a long-term (1996–2002) irrigation experiment conducted in the north-east of Brazil (3° 26′ S 39° 08′ W; alt. 31 m) were reported by Oliveira *et al.* (2006). The climate of this important cashew-growing, predominantly rain-fed area is characterised by a dry season lasting from July to December. The average annual rainfall is about 1000 mm, but is very variable (from 600 to 1500 mm during the seven years the experiment covered). The experiment compared the responses of three dwarf genotypes (CCP 09, CCP 76 and CCP 1001, grafted onto seedlings and spaced at 7 × 7 m) to three irrigation regimes, together with an unirrigated control treatment. The soil was described as a deep, sandy red-yellow podzol. Three irrigation frequencies were compared, beginning when the trees were two years old. Trees were irrigated when the cumulative evaporation from a USWB Class A pan reached 10 mm (on average over the seven years this equated to daily irrigation), 30 mm (three-day intervals) and 50 mm (five-day intervals). In order to maintain the soil water potential above -20 kPa in the top 0.5 m of the root zone in the wettest (10 mm) treatment, adjustments were made each month based on tensiometer readings, All three irrigation treatments received the same total amount of water over a season. For fully developed trees this totalled 400 to 500 mm each year. Water (with fertiliser) was applied through a single micro-sprinkler per tree. Unirrigated treatments received the same total amount of fertiliser.

The three clones differed in their responses to irrigation. Beginning in the fourth year after planting, irrigation increased yields of ‘nut-in-shell’ for two of the cultivars (CCP 09 and CCP 76). Over the seven years this increase averaged +77%, namely from 1054 kg ha^{-1} (unirrigated) to 1872 kg ha^{-1} (mean for all three irrigated treatments). For cultivar CCP 1001, the yields from the rain-fed and irrigated treatments were statistically similar, 1627 kg ha^{-1} (unirrigated) and 1848 kg ha^{-1} (irrigated). The water productivity (for ‘nut-in-shell’ and irrigation) averaged over seven years for the two responsive cultivars equates to about 2.6 kg ha^{-1} mm^{-1} (0.26 kg m^{-3}). The yield increase was the result of an increase in the number of nuts. The individual nut weights were not affected by the irrigation treatments. There was evidence of alternate bearing, with good years followed by less good years, regardless of the treatment combination. Initially, there was large variability in the data (coefficient of variation (CV) = 30%), but there was progressive improvement so that by year seven the CV had declined to 14%. No mention was made of cashew apple production.

Australia

On a commercial estate in northern Australia, Schaper *et al.* (1996) compared the yield responses of cashew (cv. BLA 39–4) to three irrigation regimes over two years (1988 and 1989). The grafted trees had been planted in 1986, at a 7 × 7 m spacing, in a deep (>4 m), sandy soil with a low water-holding capacity (73 mm m^{-1}). For two years after planting, all the trees were irrigated (with under-tree micro-sprinklers) at the rate of 40 mm $week^{-1}$. During 1988 the differential treatments were introduced, namely: irrigated throughout the dry season at 43 mm $week^{-1}$ in 1988 and at 64 mm $week^{-1}$ in 1989; irrigated weekly from flowering to harvest at the same two rates and an unirrigated control. Nut-in-shell yields were similar in both years for all three treatments, averaging 4.23 kg $tree^{-1}$, but the components of yield differed. Thus, there were 19% more nuts in the unirrigated trees (1133 nuts $tree^{-1}$) compared with both irrigated treatments (954 nuts $tree^{-1}$) – as a result of having fewer staminate flowers (see above). But irrigation increased individual nut weight from 3.7 g to 4.5 g. Irrigation also increased kernel yield (from 1.16 to 1.36 kg $tree^{-1}$), kernel weight (1.04 to 1.49 g) and kernel recovery (from 27% to 32%). The authors concluded that, despite the low yields from these three-year-old trees, irrigation of mature cashew orchards was justified (for greater kernel yield and better quality) in the tropical regions of northern Australia, but that it was not necessary to begin irrigating before the trees flowered.

In north Queensland (17° S 145° E), where the dry season lasts from April to December, there was a highly significant linear relation between nut yield after drying (recorded over three years of the experiment) and the water applied (irrigation plus rainfall from January to September: range covered = 25–50 m^3). Rainfall during the main harvest period, October to December, was ignored.

$$Y = -106(\pm 18) + 5.77\ (\pm 0.5)X; n = 90; \quad r^2 = 0.60$$

where Y = yield of nuts (g m^{-2} crop surface area) and X = water applied (m^3 $tree^{-1}$).

Yield was expressed on a crop surface area basis to allow for trees of different sizes. Extrapolation of the model suggests that 18.4 m^3 of water are required before a tree yields any nuts. Then, for every cubic metre of irrigation (or rain) applied above this base level, there is a yield increase of about 6 g m^{-2}. Kernel recovery (the proportion of the nut weight made up by the kernel) averaged about 33% across all treatment combinations (Blaikie *et al.*, 2001).

The results of an irrigation experiment with four-year-old trees growing on a clay soil in the Northern Territory, Australia (managed by N.K. Richards) were summarised by Grundon (1999). Yields of nut-in-shell were similar when irrigation was applied after the cumulative evaporation from a USWB Class A pan had reached 150 or 300 mm.

But yields declined (fewer nut-in-shell) if irrigation was withheld until cumulative evaporation had reached 600 mm. Reductions in the frequency of irrigation did not affect the depth of water extraction, but the zone of water depletion increased laterally.

Richards (1993) makes the point very clearly that large commercial yields and good kernel recovery rates require adequate water *and* nutrient inputs. Irrigation can be restricted to the period beginning with the commencement of flowering to harvest.

Observations made in Australia indicate that the water table should not be closer to the surface than about 1.5 m (Grundon, 1999).

Summary: water productivity

1. In Brazil, irrigation resulted in a cumulative yield benefit of +77% over seven years (above a base yield of 1054 kg ha^{-1}) for two dwarf clones. A third clone yielded more than the other two under dry conditions, but gave the same yield when irrigated.
2. The average water productivity (nut-in-shell) for the two clones that responded to irrigation was about 0.26 kg m^{-3} (irrigation water).
3. The yield increase was due to more, not larger, nuts being harvested.
4. Alternate bearing confounded the evaluation process.
5. In northern Australia, experiments suggested that there was no yield benefit from irrigation before cashew trees flowered.
6. Benefits from irrigation from flowering onwards included larger yields (+43%) as a result of bigger nuts. Kernel recovery was also improved. In contrast to Brazil, the unirrigated trees in Australia had more nuts (+19%) than the irrigated trees (as a result of having fewer male flowers).
7. A linear relationship (slope of line = 6 g m^{-2}) was obtained between nut yield, expressed on a crop surface area basis, and water applied (irrigation and rainfall). Unfortunately, there is no comparable figure.
8. Cashew can survive long periods without rain before flowering, but irrigation is beneficial from flowering until harvesting begins. There must be an interaction with plant density, but this does not seem to have been studied.
9. The cashew is notorious for the great variability that exists between trees and even within a single tree, making experimentation difficult (C.P. Topper, personal communication).

Irrigation systems

There is one report comparing two systems of irrigation for cashew. Two examples of general recommendations to growers on how to irrigate cashew are also summarised here. In addition, an evaluation of several soil and water conservation practices on steep slopes in India is described.

The experiment in north Queensland described above included a comparison between sprinkler (not specified, presumed to be under-tree micro-sprinklers) and drip irrigation, as well as several irrigation treatments (Blaikie *et al.*, 2001). Similar linear functions between yield and water applied were derived when the two irrigation methods were analysed separately, but with different slopes (sprinkler $+5.24X$; drip $+7.45X$). The same marginal yield response occurred regardless of when the irrigation was applied during the dry season, or where the dripper line was placed relative to the tree trunk. The productivity of drip irrigation was marginally (5%) greater than that of sprinklers. Each dripper or pair of drippers wetted an area of soil of about 1 m^2, whereas the sprinkler wetted 28 m^2.

In Binh Phoc province, Vietnam (11º 45′ N 106º 43′ E), the advice is to apply 100 L $tree^{-1}$ once every 7 to 10 days during flowering, and 200 L $tree^{-1}$ once every 15 to 20 days during nut setting. The recommendations are based on the results of an irrigation experiment (details were not presented) with six-year-old trees (Peng *et al.*, 2008). These rates are equivalent to14 or 10 L d^{-1} and 13 or 10 L d^{-1} respectively.

In India, where cashew cultivation is generally carried out under rain-fed conditions, the advice to growers is similar in terms of the quantities of water to apply, but again the tree density is not specified.

In homesteads, it is advisable to give some supplementary irrigation from January to March (flowering and fruit set stages). A water application of about 200 L $tree^{-1}$ every fortnight (*equivalent to 14 L* d^{-1}) had been found to double cashew yields in trials conducted at the National Research Center at Puttur (12º 45′ N 75º 12′ E). In the sandy tracts of the east coast, although frequency and quantity of water applied varies, trees are watered during the summer months (Rao, 1998).

The evidence base for this advice is not cited. It is questionable whether smallholders will carry large quantities of water to trees.

Soil and water conservation

In India, where cashew is grown on the steep slopes of the west coast region, water stress occurs during February to May, despite an annual rainfall of 3000–3500 mm (Rejani and Yadukumar, 2010). The period of water stress occurs when the crop is in the flowering and fruit set stages of development. A soil water deficit of up to 300 mm can occur at this time. A number of soil and water conservation techniques were evaluated on a very steep (up to 40%) eroded slope at Puttur over a seven-year period from planting in 2003 up to 2010. Yields, and other growth parameters, were recorded for five years (2005/6 to 2009/10). The two most effective conservation techniques were a ‘modified crescent bund’ and ‘coconut husk burial’. These both reduced runoff from 37% of the annual rainfall (mean total 3011 mm) in the control to 20% and 22%, respectively. The amount of eroded soil was reduced by about 50% from 9.7 t ha^{-1} y^{-1} (control) to 4.6 and 4.8 t ha^{-1} y^{-1} in the same two conservation treatments. There was also a yield benefit: total yields of ‘nut-in–shell’ over the five years were increased by about 33% from 4.9 t ha^{-1} to 6.45 and 6.60 t ha^{-1}. A cost–benefit analysis suggested that an investment in conservation measures of the sort described was financially worthwhile. The question remains as to whether farmers perceive the extra work involved to be justified.

Conclusions

Research on many aspects of cashew nut production is normally undertaken at a national level, although the integrated crop management project in Tanzania is an example of international cooperation (Martin *et al*., 1997). In the same way, detailed studies on the developmental physiology, water relations and irrigation need of this crop are largely confined to Brazil (where the crop is believed to have originated) and Australia (where cashew is still an emerging commercial crop). This is an interesting example of two extreme positions from which to undertake research. As an indigenous species, Brazil has the opportunity to exploit cashew's genetic diversity, and to support a successful commercial sector looking to do even better. In contrast, Australia is looking to establish a new industry, but with little background information from which to work. Very wisely, Australia began the process by establishing a searchable database

Figure 3.5 The swollen pedicel known as the cashew apple is a source of juice high in vitamin C – Sierra Leone (RCC). See also colour plates section.

of the international research literature on cashew (mainly covering the period from 1979 to1998, both the formally published and the ‘grey’ literature).This was then reviewed in detail to see what lessons there were for Australia, and to identify the likely limiting factors that needed to be addressed as a priority (Grundon, 2000).

Despite cashew having the reputation of being a drought-tolerant crop, water was expected to be one of the principal limiting factors. Research in both Brazil and Australia has focused on the limitations to productivity that climate, and water availability in particular, might impose. The capacity of mature trees to survive a long dry period prior to flowering, without loss of yield, has been largely established, as long as water is freely available from flowering to the start of harvest. The important role that the stomata play in maintaining a favourable leaf water status under dry (soil and air) conditions has been demonstrated, at least in part. However, reliable estimates of water productivity have yet to be established. This is partly because few (expensive) long-term field experiments have been undertaken. There is some evidence in Brazil that cultivars differ in their capacity to tolerate dry conditions/respond to irrigation. It can be expected that yield responses to water will vary with the tree density. There is a continuing need to develop a reliable method with which to estimate crop water requirements, to identify where and when irrigation of cashew is likely to be justified, and to develop a practical irrigation schedule. The needs of the different farming systems within which cashew is a component will need to be considered. Cashew should not be allowed to remain as ‘a poor man’s crop and a rich man’s food’. It is a very valuable, internationally traded commodity that can contribute to the improvement of the livelihoods of many people who are involved in its production across the world (Figure 3.5). International cooperation on research into the topics covered in this chapter would benefit everyone.

Summary

The centre of origin of cashew is believed to be Brazil, from where it has spread since the sixteenth century throughout the tropics. In recent years, Vietnam has surpassed India to become the world’s largest producer of the cashew nut. Most of the research on the water relations of cashew has been done in Brazil, where it is both a large-scale commercial and a smallholder crop, and in Australia where cashew is a possible emerging new crop. There are two ‘types’ of cashew, ‘talls’ and ‘dwarfs’. Both are evergreen trees in which vegetative growth occurs in a series of flushes. Flowers form annually on the end of branches in the dry season, and flowering continues for two to four months. It then takes about two months from pollination for the nut to mature. Roots can extend to great depths (>5 m), whilst cashew’s wide-spreading rooting habit is critical to its successful adaptation to semi-arid/dry conditions. The optimum temperature for CO_2 assimilation is in the range 25–35 °C. Progressive closure of the stomata occurs at saturation deficits of the air >1.5 kPa. In the field differences in rates of gas exchange between irrigated and unirrigated cashew trees only become apparent three or four months after the end of the rains, the stomata playing an important role in maintaining a favourable leaf water status in dry conditions. Sap flow measurements indicate transpiration rates of 20–28 L d^{-1} $tree^{-1}$. Irrigation can be beneficial during the period from flowering to the start of harvest, but reliable estimates of water productivity have yet to be established. The best/only estimate is 0.26 kg (nut-in-shell) m^{-3} (irrigation water). There is a continuing need to develop a method to estimate the water requirements of cashew, to identify where and when irrigation of cashew is likely to be justified, and to develop a practical irrigation schedule.

Endnotes

1 Botanically a nut is a dry, indehiscent single-seeded fruit.
2 A Brazilian ecosystem similar to savannas.

4 Citrus

Introduction

The cultivated *Citrus* species are believed to be native to tropical and subtropical regions of south-east Asia (probably north-eastern India, Burma and southern China), where they have been cultivated since remote times. It seems probable that citrus originated in the drier monsoon areas rather than in tropical rainforests since it does not normally grow as well in the very humid tropics. Man took into cultivation those species with palatable juice. Natural hybridisation then occurred between cultivars and species, producing an array of complex hybrids. The cultivated *Citrus* has now spread throughout the tropics and subtropics. Most of the commercial production is now in subtropical regions at latitudes greater than 20º N and 20º S, but less than 45º N and 35º S, and between sea level and 600–750 m (Purseglove, 1968; Roose *et al*., 1995).

Several reviews have been published on aspects of the water relations of citrus, but only one relatively recently. This was a detailed review of factors influencing photosynthesis in citrus grown in the subtropics (with particular reference to Brazil) by Ribeiro and Machado (2007)[1]. Previously, Doorenbos and Kassam (1979) had focused on practical ways of estimating the yield responses to water, whilst Kriedemann and Barrs (1981) wrote a detailed and comprehensive review of the water relations of citrus, but without drawing clear, useful conclusions. Later, Jones *et al*. (1985) reviewed, from a fundamental perspective, the physiological aspects of the control of the water status of citrus alongside other temperate and subtropical fruit trees. Shalhevet and Levy (1990) focused on the irrigation of *Citrus* spp., whilst Syvertsen and Lloyd (1994) concentrated on their physiological responses to the environment, with a focus on gas exchange. However, most recently, Goldhamer *et al*. (2012) have summarised the responses of citrus to water deficits and described the development of water production functions in the FAO Irrigation and Drainage Paper 66, entitled *Crop Yield Response to Water*. To minimise duplication, the principal points of interest arising from these reviews are briefly summarised at relevant points in the body of this chapter, which concentrates on research published since 1990.

Species and centres of production

The common cultivated *Citrus* species include the following, which are listed with their principal uses and their important cultivars:

- Sweet orange (*C. sinensis*): fresh fruit, juice, squash, flavouring, oils, pectin, pulp (residue left after squeezing for juice) and peel used as cattle feed. Cultivars: Valencia, Washington Navel.
- Grapefruit (*C. paradisi*): fresh fruit, juice. Cultivars: Marsh, Thompson (Figure 4.1).
- Lemon (*C. limon*): drinks, flavouring, garnish, cosmetics, oil, citric acid, pectin. Cultivars: Eureka, Lisbon, Villafranca.
- Lime (*C. aurantifolia*): fresh fruit, flavouring, drinks, marmalade, lime oil (from peel). Cultivar: Mexican.
- Mandarin/tangerine (*C. reticulata*): fresh fruit. Cultivars: Satsuma group, mandarins (Emperor) and tangerines (Clementine)
- Seville (sour) orange (*C. aurantium*): marmalade, flavouring, liqueurs, oils for perfumery. Extensively used as a rootstock for lemon, sweet orange and grapefruit.
- Pomelo (pummelo) (*C. grandis*): dessert fruit.
- Citron (*C. medica*): flavouring.

In 2008, the total planted area of citrus was about 5.4 million ha, of which oranges covered 4.2 million ha, lemons and limes together 1.02 million ha and grapefruit with pomelo 0.25 million ha. Oranges represented 80% of the total (= 86 million t) world

Figure 4.1 Pink-fleshed grapefruit – Swaziland (MKVC).

Citrus production, lemons and limes combined 15% and grapefruit (with pomelo) 5%. The largest producers were as follows:

- *Oranges*: Brazil (18.5 million t) followed by the USA, India, Mexico and China.
- *Lemons and limes*: India (2.4 million t), followed by Mexico, Argentina, Brazil and China.
- *Grapefruit*: the USA (1.4 million t) followed by China, Mexico, South Africa and Israel (FAOSTAT, 2011).

The different species are initially considered together and later individually.

Crop development

To minimise the duration of the juvenile phase of growth, when the trees are unproductive, and to impart other characteristics, most citrus orchards are now planted with composite plants in which the favourable attributes of a scion are matched with those of a rootstock (Davies and Albrigo, 1994). Important rootstocks include the following:

- Rough lemon (*C. jambhiri*)
- Alemow (*C. macrophylla*)
- Rangpur (*C. limonia* hybrid)
- Sour orange (*C. aurantium*), (Figure 4.2)
- Trifoliate orange (*Poncirus trifoliata*)
- Citranges; intergeneric hybrids of sweet orange and trifoliate orange.

Figure 4.2 Seville or sour orange tree, used extensively as a rootstock – Turkey (HDT).

Vegetative growth

Citrus species are small, evergreen shrubs or trees. In the subtropics, shoot growth occurs in a series of discrete flushes initiated by a rise in air temperature (>12.5 ºC) or, in the tropics, where the flushes are less discrete, by the availability of water (Davies and Albrigo, 1994). Seasonal variations in the vegetative growth of Hamlin sweet orange in subtropical Brazil (22.5º S) have been described by Ramos *et al.* (2010), whilst the influence of water on the growth and development of young trees is illustrated by the following experiments in Florida and Spain.

Irrigation, at up to four- to six-day intervals, of Hamlin sweet orange (*C. sinensis*) grafted on to a sour orange rootstock (*C. aurantium*), during the first year after planting on a sandy soil, enhanced many components of vegetative growth, including leaf area, canopy volume and trunk cross-sectional area. The date of initiation of the first (spring) growth flush was little affected by the irrigation treatment, in each of the three years the experiment was repeated, but the second (summer) and third (autumn) flushes were delayed, or failed to happen, when irrigation intervals were extended (Marler and Davies, 1990).

Similar results were obtained in Spain with eight-year-old Clementina de Nules mandarin trees (*C. clementina* grafted on to Carrizo citrange rootstock) by Ginestar and Castel (1996). Withholding irrigation in the spring (1 March to 13 June) had no effect on shoot extension in the first (spring) flush, but water stress in the summer (14 June to late July/early August) reduced shoot growth in the second (summer) flush or even stopped it occurring. Water stress in the late summer/early autumn had a similar effect, but trees irrigated at this time, having previously been droughted, produced an abundant second (summer) flush composed mainly of flowers. Shoot elongation ceased when the integrated shoot water potential reached about 35 day MPa (average pre-dawn leaf water potential within a given interval summed above maximum recorded value, see below).

Summary: vegetative growth (includes previous reviews)

1. Shoot growth occurs in distinct flushes initiated by a rise in temperature (subtropics) or availability of water (tropics) (Jones *et al.*, 1985). Water stress can delay the initiation of the summer and autumn flushes.
2. Shoot and root growth alternate (Jones *et al.*, 1985; Bevington and Castle, 1985; Syvertsen and Lloyd, 1994).
3. Although citrus cultivars are evergreen, leaves are shed throughout the year and continual leaf replacement occurs as the trees grow. The age at which a leaf drops is variable, but is usually between nine and 24 months: leaves of all sizes are shed generally in the months immediately following blossoming (Kriedemann and Barrs, 1981).
4. Leaf abscission is observed in field-grown trees when pre-dawn leaf water potentials are around -2.75 MPa (Ribeiro and Machado, 2007).
5. There are two abscission zones: the base of the petiole and (at times of severe stress) between the lamina and the petiole (Kriedemann and Barrs, 1981).

6. Canopy development and stem growth are both restricted by water stress (Kriedemann and Barrs, 1981; Shalhevet and Levy, 1990).Water stress during periods of vigorous vegetative growth should be avoided (Doorenbos and Kassam, 1979).
7. There is evidence of a direct causal link between stimulation of ethylene production by water stress and citrus leaf abscission (Kriedemann and Barrs, 1981).
8. There is a poor correlation between trunk size and canopy development (Shalhevet and Levy, 1990).
9. Sun-exposed leaves represent only about 20% of the total leaf area of an orange tree canopy. The internal canopy does not receive more than 10% of the total photosynthetic photon flux density (PPFD) received at the canopy surface. Citrus leaves can reach temperatures of around 42 ºC in the summer (Ribeiro and Machado, 2007).
10. Excess vegetative growth can reduce fruit yields (Shalhevet and Levy, 1990).

Flowering and fruiting

Iglesias *et al*. (2010) have recently published an overview of the physiology of flowering and fruiting in *Citrus*. According to this report, it takes two to five years from planting for a citrus tree to reach a stage when it can produce flowers. In subtropical areas, flowering takes place after a period of bud quiescence as a result of exposure to low temperatures in winter. In the tropics, and in areas with a dry season, rehydration after a period of water stress triggers the flowering process. The inflorescence may be leafless (flower buds only) or leafy (vegetative and flower buds both present on the same shoot). The degree of fruit set is dependent on the type of inflorescence formed. In general, leafless inflorescences emerge first and contain a bouquet of flowers with a low likelihood of setting fruit. By contrast, flowers in leafy inflorescences are commonly associated with a better fruit set (the fewer the number of flowers on a stem the higher the proportion that form fruits). In seeded cultivars, pollination (mainly by bees) and fertilisation are necessary to initiate fruit development, but not in the seedless cultivars (Iglesias *et al*., 2010). The practical aspects of evaluating the intensity of flowering in citrus has been studied by Ribeiro *et al*. (2008).

In most *Citrus* species grown in the subtropics, flowering takes place in the spring and the subsequent formation of fruit can extend, depending on the cultivar, until midwinter. *Citrus* fruits are a special type of berry (known as a hesperidium), with two morphologically distinct regions: the pericarp (commonly known as the peel or rind) and the endocarp (the juicy pulp, which is edible) (Figure 4.3).

Growth and development of a fruit follows a typical sigmoid curve that can be divided into three phases. The initial phase following anthesis is a two-month period of cell division and slow growth. The second phase is a four- to six-month period of rapid growth as the cells enlarge and accumulate water. Finally, there is the maturation period (a non-climacteric process in citrus) when fruit growth slows and external (colour change) and internal (a decline in acidity and an increase in sugars) ripening processes occur (Iglesias *et al*., 2010).

Citrus trees bloom profusely (e.g. for sweet orange as many as 250 000 flowers tree^{-1} can be formed). This number is considerably reduced by the abscission of flower buds,

Figure 4.3 Red-fleshed sweet orange. Citrus fruits are a special type of berry with two distinct regions, the pericarp, or peel, and the endocarp, the juicy pulp, which is edible – Ethiopia (HDT). See also colour plates section.

flowers and ovaries, mostly at the beginning of phase 1. In addition, developing fruits are lost during phase 1 (a process known as the June drop in the northern hemisphere, and as the December drop south of the equator). Although fruit abscission is considerably less during phases 2 and 3, less than 1% of flowers reach maturity (Iglesias *et al*., 2010). Previously, Erickson (1968) had presented detailed data on the number of flower buds per tree (Washington Navel, 200 000 tree^{-1} and Valencia, 70 000 tree^{-1}) and the number of mature fruit (419 and 708 tree^{-1}, respectively). For these two cultivars of sweet orange this is equivalent to 0.2% and 1.0% success rates, respectively. The control of fruit set and abscission in citrus is complex, being regulated by genetic, metabolic and environmental factors acting sequentially, simultaneously or superimposed on each other, and is not yet fully understood (Iglesias *et al*., 2010).

The influence of water availability and its timing on the flowering process is illustrated by the observations made in Spain on clementine trees by Gonzalez-Altozano and Castel (2000). Withholding water during the spring (flowering and fruit set phase) reduced shoot extension in the first flush, and increased the loss of flower buds and small fruits when full irrigation was introduced in early summer (relative to the well-watered control treatment). This treatment also resulted in more off-season flowering in the second and third flushes, which led to 10% off-season fruit (with no commercial value). Similar treatment combinations applied during the summer (early fruit enlargement phase) resulted in some off-season flowering in the autumn flush, but not as much as when the treatments were applied during the fruit growth and maturation phases.

The abscission of leaves and fruits occurs suddenly after their re-hydration following the alleviation of water stress. The process is associated with increases in the content of abscisic acid (ABA) in the roots and the subsequent accumulation of ethylene in the aerial parts of the plant (Iglesias *et al.*, 2010).

The relative sensitivity of fruit expansion to water availability is shown by the results of a series of field trials in Israel. Fruits (of grapefruit) continued to accumulate dry matter when subjected to water stress, even when the fruits no longer increased in volume, indeed even when shrinkage occurred (Cohen and Goell, 1988). Upon re-watering, fruits from droughted trees expanded faster than those from trees that had been watered regularly, reaching a final size determined (in part) by the quantity of accumulated dry matter.

Subsequently, Huang *et al.* (2000) investigated the mechanisms responsible for this phenomenon of compensatory growth. Mild water stress was imposed on pot-grown tangerine trees (*C. sinensis* Blanco cv. Zhuju) during the early juice sac expansion phase. Water stress resulted in a decline in the fruit water potential as a result of the loss of water from the fruit to transpiring leaves, together with an increase in the soluble solid content of the fruit juice (and also the fruit skin), causing the osmotic potential to drop (osmotic adjustment). There was also evidence of cell wall loosening in the fruit skin, which caused a further reduction in fruit water potential (loss of turgor). As a result of these changes in water potential, the fruits expanded faster than those in the well-watered control treatment upon re-watering, and grew to a larger size. The timing and duration of the stress is critical to this (compensatory) process (Figures 4.4 and 4.5).

Figure 4.4 Water-stressed grapefruit tree – Nigeria (MKVC).

Figure 4.5 Severely water stressed grapefruit tree – Nigeria (MKVC).

Summary: flowering and fruiting (mainly from previous reviews)

1. For flowering to occur a 'rest period' is necessary. This can be provided by low temperature (in the subtropics) or by drought (tropics) (Doorenbos and Kassam, 1979).
2. Rain/irrigation after drought induces flowering (which is undesirable in mid-season) (Shalhevet and Levy, 1990).
3. In (some parts of) the subtropics, the 'rest period' is induced by two successive months with mean air temperatures (presumably) at 10 °C (or less), and in the tropics by water stress (monthly rainfall less than 50–60 mm). Too much stress can result in the production of too many flowers, which may lead to biennial bearing (Doorenbos and Kassam, 1979).
4. For lemons, allowing a water deficit to occur in the summer is commonly used to initiate flowering for year-round fruit production (Doorenbos and Kassam, 1979).
5. Water stress during flowering increases shedding of flower buds and flowers before fruit is set. These effects are due to weakening of the (two) pre-formed abscission zones at the points of attachment (Jones *et al.*, 1985). Water stress during flowering reduces fruit set, and can lead to a heavy June/December drop (Doorenbos and Kassam, 1979).
6. Water stress during the early yield-formation phase (June or December, depending on latitude) can increase fruit shedding and reduce the rate of fruit growth (Doorenbos and Kassam, 1979).
7. Water stress during the fruit expansion phase affects final fruit size (but can increase the content of the total soluble solids (TSS) and acids) (Doorenbos and Kassam, 1979).

8. In addition, severe stress during fruit expansion can trigger flowering, which is undesirable at this phase (except for lemons) (Doorenbos and Kassam, 1979).
9. Satsuma fruits stop growing when the pre-dawn leaf water potential reaches −0.8 MPa (Kriedemann and Barrs, 1981).
10. From flowering to fruit maturity takes 7–14 months (Doorenbos and Kassam, 1979). Less than 1% of flowers (up to 250 000 tree^{-1}) produce fruit.
11. Lemon has a longer flowering period than other *Citrus* spp., and its fruit is harvested throughout the year (Doorenbos and Kassam, 1979).

Roots

Most *Citrus* spp. have a single tap-root, with lateral roots forming a dense mat in the surface layers (Purseglove, 1968; Morgan *et al*., 2007). Despite the important role that rootstocks play in their culture, there is little recent published research on root systems. A few examples are given below.

In a comparison between two tree planting densities in Florida (cv. Hamlin orange on Milam lemon rootstock, seven-years-old; drip irrigated), roots were traced to depths of 1.65 m (the maximum depth of observation) in both populations. Root densities were greater in the high-population treatment (889 trees ha^{-1}) than in the lower-population treatment (370 trees ha^{-1}) at all depths, but particularly in the top 0.5–0.7 m of soil (Whitney *et al*., 1991).

In Florida, Morgan *et al*. (2007) excavated the root systems of 18 trees with tree canopy volumes (TCV) ranging from 2.4 to 34.3 m^3, on two different rootstocks and growing in well-drained sandy soils. The roots were sampled in a systematic pattern extending 2 m away from the trunk and 0.9 m deep. Trees grown on Swingle citrumelo (*C. paradisi* Macf. × *Poncirus trjfoliata* (L.) Raf) rootstocks had significantly greater fibrous root length density (FRLD) in the top 0.15 m (up to 2 cm cm^{-3}) than trees on Carrizo citrange (*C. sinensis* (L.) Osbeck × *P. trifoliata* (L.) Raf.) (up to 1.2 cm cm^{-3}). Conversely, Carrizo citrange had greater FRLD from 0.15 to 0.75 m below the soil surface (up to 0.6 cm cm^{-3} cf. up to 0.3 cm cm^{-3}). The FRLD was significantly greater for ‘Hamlin’ orange trees grown on Swingle citrumelo rootstock at distances <0.75 m from the tree trunk compared with those on Carrizo citrange. Fibrous roots of young citrus trees developed a dense root mat above soil depths of 0.3 m that expanded both radially and with depth over time as the trees grew and the TCV increased.

In Brazil, roots of seven-year-old irrigated lime trees (*C. latifolia*), grafted on to *C. limonia* rootstock, reached depths of 1.5 m, with the bulk of the roots in the top 0.40 m (Marin and Angelocci, 2011). Similar observations were made by Hutton and Loveys (2011) on mature Navel oranges (*C. sinensis*) in New South Wales, Australia.

Measurements made in Bahia State, Brazil by Santana *et al*. (2006) showed how root densities varied (range from 0.75 cm cm^{-3} to 0.05 cm cm^{-3}) with the physical properties of the soil (Yellow Latosol and a Grey Argosol).

Summary: roots (almost entirely based on previous reviews)

1. Seedlings have a well-defined tap-root (unless it is damaged in the nursery) (Kriedemann and Barrs, 1981).
2. There is uncertainty about root depth and distribution. As a general rule roots extend in depth to 1.5 m. However, roots of mature trees have been found at 3–5 m (with a rough lemon rootstock) (Kriedemann and Barrs, 1981; Shalhevet and Levy, 1990).
3. Fibrous roots occur in bunches on pioneer/structural roots, with the greatest mass in the top 0.4 m (Kriedemann and Barrs, 1981).
4. Root hairs are numerous but they are abnormally short (Kriedemann and Barrs, 1981).
5. Root length densities vary with soil depth, distance from the trunk, soil physical properties and cultivar.
6. The scion, as well as the rootstock, influences the root system to varying extents (e.g. grapefruit has a greater effect on a root system than does orange) (Kriedemann and Barrs, 1981).
7. For root growth to occur the minimum soil temperature is reported to be *c*. 6ºC, the optimum *c*. 26ºC, and the maximum *c*. 37ºC (Kriedemann and Barrs, 1981).
8. Interconnections in the root system appear to ensure that water applied to one part of the root system becomes available to the whole tree (Kriedemann and Barrs, 1981). The main resistance to water flow in a plant is in the root system (Jones *et al*., 1985).
9. Vesicular-arbuscular mycorrhizae are believed to increase water and nutrient uptake by plant roots (Jones *et al*., 1985). The mucilage present on young feeder roots contains microorganisms (Kriedemann and Barrs, 1981).

Plant–water relations

Stomata

While *Citrus* is considered to be a typical mesophyte (not specifically adapted to wet or dry conditions), the leaves have many xeromorphic characteristics. Their upper surface, for example, is covered by a thick waxy cuticle. Stomata occur mainly on the lower (abaxial) leaf surface, at a density of 800 mm^{-2}, compared with 40 mm^{-2} on the upper (adaxial) surface (Spiegel-Roy and Goldschmidt, 1996). By contrast, Erickson (1968) recorded stomatal densities for the abaxial surface of between 360 and 620 stomata mm^{-2} for a selection of *Citrus* spp. at four locations in California.

In Brazil, stomatal conductances were observed to decline rapidly once the leaf water potential (as recorded at 1400 h) was less than -1.0 MPa. In this pot experiment with 30-month old Pera orange trees (*C. sinensis*) grafted onto Rangpur lemon rootstock (*C. limonia*), the concentration of abscisic acid in the leaves began to increase at the same level of water stress (Gomes *et al*., 2004).

In a controlled-environment experiment in Florida, Brakke and Allen (1995) confirmed previous reports that midday reductions in stomatal conductance and carbon dioxide assimilation rates in *Citrus* spp. are associated with high temperatures/dry air. When soil water was not readily available, photosynthesis by *Citrus* was more sensitive (reduced carbon dioxide uptake) to high temperatures and saturation deficits (37 ºC/3.6 kPa) than at lower values (29 ºC/2.4 kPa). In Brazil, Magalhães Filho *et al*. (2009) demonstrated the role that the soil/substrate temperature can play in controlling gas exchange, photochemical activity and water relations of sweet orange in a controlled-environment study (root temperatures compared, 10, 20 and 30 ºC; air temperature = 25/20 ºC day/night).

By monitoring sap flow (using the compensation heat-pulse technique) as a measure of transpiration, Nicolás *et al*. (2008) were able to show the control that the stomata exerted on transpiration by young lemon trees growing in the open (i.e. there was strong coupling of the crop canopy with the environment).

The level of control was less with plants artificially shaded (with nets), although shading improved instantaneous water-use efficiency by reducing transpiration whilst maintaining photosynthesis.

Sap flow gauges were also used by Oguntunde *et al*. (2007) to estimate transpiration by seven-year-old sweet orange trees in a rain-fed orchard in tropical Ghana (07° 20′ N 1° 16′ W; alt 210 m) to develop a model for predicting stomatal control of transpiration. When well watered, the saturation deficit of the air was the dominant regulator of transpiration (recorded at half-hour intervals), explaining 80% of the variation in canopy conductance, with partial stomatal closure occurring at saturation deficits in excess of 1.2 kPa. There was also a hyperbolic relationship between transpiration and solar radiation with light saturation in the region of 400 W m^{-2} (PAR equivalent = 900 μmol m^{-2} s^{-1})

Through their impact on the hydraulic conductivity of a tree, rootstocks can influence the rate of sap flow in the scion. For example, in Japan, Yonemoto *et al*. (2004) showed how sap flow rate differed in branches of Shirakawa Satsuma mandarin trees (*C. unshiu*) depending on the rootstock. Sap flow rates were least with the dwarfing rootstock ‘Flying Dragon’ trifoliate orange (*Poncirus trifoliata*, cv. Monstrosa) and greatest with trifoliate orange (*P. trifoliate*). Sap flow rates were also consistently less in trees bearing a large quantity of fruit compared with those with a smaller yield.

Osmotic adjustment

There is some limited evidence that osmotic adjustment may play a role in mitigating the effects of drought stress. For example, in Spain, Rodríguez-Gamir *et al*. (2010) compared the responses to extreme drought stress of the *Citrus* hybrid rootstock Forner-Alcaide no. 5 (FA-5) with those of its parents, *Cleopatra mandarin* and *Poncirus trifoliate* as nine-month-old seedlings, or when each rootstock was grafted with Valencia orange scions as 15-month-old trees. The plants were grown in coarse sand in pots in a greenhouse and watered with nutrient solution. Drought stress was imposed by withholding irrigation. Based on a series of detailed measurements of plant water status and gas exchange processes, they concluded that FA-5 was more resistant to drought than either of its parents. As a rootstock, it also influenced the performance of the scion through the process of osmotic adjustment. It remains to be seen how representative these results derived from pot experiments are of field conditions where water stress develops more slowly.

Osmotic adjustment was also observed in a short-term (four-month) field experiment in south-eastern Spain. Mature Fino 49 lemon trees (*C. sinensis*, grafted on to *C. macrophylla* Western rootstock), when irrigated with saline water, maintained leaf turgor and gas exchange processes through osmotic adjustment (uptake of Cl^- ions). By contrast, there was no evidence of osmotic adjustment in droughted trees, which reacted to water deprivation by closing the stomata to restrict transpiration, whilst maintaining leaf turgor (Pérez-Pérez *et al.*, 2009b).

Stem shrinkage

Stem water potentials are also related to the degree of stem shrinkage that occurs when a tree experiences water stress. Thus, in Murcia, Spain (38° 6′ N 1° 2′ W), Ortuño *et al.* (2009) showed how there was a close negative linear relationship between maximum daily trunk shrinkage (MDS, that is the difference between the maximum trunk diameter early in the morning and the minimum trunk diameter early in the afternoon) and stem water potential. This relationship, which was developed for well-watered lemon trees (*C. limon* cv. Fino) grafted on to sour orange rootstock (*C. aurantium*), was independent of season and crop load. This paper followed earlier ones describing the relationships between various plant-based indicators of water stress, as recorded on potted young lemon trees (*C. limon*), also grafted on to sour orange rootstock (*C. aurantium*), grown in a greenhouse in Spain (Ortuño *et al.*, 2004) or in the field (Ortuño *et al.*, 2005). Similar preliminary results and conclusions were reported by the same team for mature lemon trees subjected to a single cycle of water stress (50 d) and a subsequent 16 d recovery period at the same site (Ortuño *et al.*, 2006a). In a separate paper, Ortuño *et al.* (2006b) presented the relationships between the same three plant water status indicators (maximum daily stem shrinkage, sap flow and stem water potential) and weather variables collected throughout a 277-day period for a mature, well-watered lemon crop. Maximum daily trunk shrinkage was again best correlated with mean daily air temperature, and sap flow and stem water potential with reference-crop evapotranspiration (ET_o). Thus, an increase in ET_o reduces the stem water potential and increases the trunk shrinkage. It was suggested that continuous sap flow and maximum daily trunk shrinkage measurements together could provide the basis for the development of automatic irrigation scheduling systems for citrus trees (see below).

Summary: plant–water relations (mainly based on previous reviews)

1. Stomata are found mainly on the lower leaf surface e.g. 800 (lower): 40 (upper) stomata mm^{-2}. Some pores are filled with loosely fitting wax plugs; there is uncertainty about whether stomata with plugs remain functional (Kriedemann and Barrs, 1981).

2. There are no active stomata on the adaxial surface of a leaf, apart from a few along the midrib. The adaxial surface is covered by a thick cuticle (Shalhevet and Levy, 1990).
3. Stomata in *Citrus* are relatively small and numerous compared with other species; the lowest recorded values are 326 stomata mm^{-2} (*C. aurantifolia*), and the highest 873 stomata mm^{-2} (*C. medica*). Leaves in the sun have a greater stomatal density than those in the shade (Kriedemann and Barrs, 1981).
4. Stomata are present on fruit at a density of *c*. 70 mm^{-2} (and function like leaf stomata) (Kriedemann and Barrs, 1981).
5. Cyclic oscillations of stomatal conductance and photosynthesis are observed in the laboratory and in the field with a periodicity of about 20–40 minutes (Kriedemann and Barrs, 1981; Syvertsen and Lloyd, 1994).
6. Epicuticular wax is present on the outermost surface of a leaf. It builds up during a period of four months, suppresses cuticular transpiration and also means that it is difficult to wet a leaf surface (Kriedemann and Barrs, 1981).
7. The highest stomatal conductances are found mid-morning (0900 to 1030 h). Earlier than this time, light intensity is the limiting factor, afterwards it is dry air (saturation deficit $>$ 1.5 kPa) (Jones *et al*., 1985; Ribeiro and Machado, 2007).
8. Stomatal conductances vary between seasons at the same photosynthetic photon flux density (PPFD), even in well-watered trees (they are lower in the winter) (Ribeiro and Machado, 2007).
9. Low air (at night) and soil temperatures in the winter are also thought to play an important role in stomatal regulation in *Citrus*, induced by hydraulic and/or chemical signals (Ribeiro and Machado, 2007; see also Magalhães Filho *et al*., 2009).
10. Photoinhibition (light-induced reduction in photosynthetic quantum efficiency) in *Citrus* occurs in warm regions during the summer, partly a consequence of the low-light saturation of photosynthesis (at about 25% of full sunlight) (Ribeiro and Machado, 2007; Syvertsen and Lloyd, 1994).
11. Both the leaf water potential (ψ_l) and stomatal conductance (g_s) are sensitive to the saturation deficit (*SD*) of the air (Kriedmann and Barrs, 1981).
12. Stomatal closure can result in higher leaf water potentials in moderately water-stressed trees compared with well-watered trees (Jones *et al*., 1985).
13. Stomata close at a ψ_l below -0.7 MPa at low *SD*, and at less than -1.2 MPa at high *SD* (based on records from Valencia orange with non-limiting soil water) (Shalhevet and Levy, 1990).
14. Diurnal changes in ψ_l are similar to those of other fruit tree species with minimum values of between -1.0 and -2.5 MPa in early afternoon (Jones *et al*., 1985).
15. Throughout a year, stem water potentials varied between -0.20 MPa (pre-dawn) and -1.75 MPa (at 1400 h) in irrigated trees, and down to -2.30 MPa in unirrigated plants (Ribeiro and Machado, 2007).
16. There is little difference between minimum ψ_l values achieved in well-watered trees in humid and arid environments, indicating effective physiological control of ψ_l through control of the rate of transpiration (Jones *et al*., 1985).

17. Transpiration by trees having a high boundary layer conductance is more sensitive to changes in total leaf conductance than are short crops with a low conductance (Jones *et al*., 1985).
18. There is only limited evidence that osmotic adjustment occurs in citrus when experiencing water stress (Jones *et al*., 1985).
19. Rootstocks can influence the rate of sap flow in the scion.
20. Stem water potential is related to the degree of stem shrinkage that occurs when a tree is subject to water stress.

Crop water requirements

In recent years, a diversity of methods has been used to measure the actual water use (*ET*) of *Citrus*. These methods include the water-balance approach (with orange) in subtropical southern Uruguay, and the aerodynamic method in Brazil (lime), Italy (clementine) and Spain (clementine). The sap-flow technique has been used to estimate transpiration (*T*) in Brazil and Italy. Lysimeters and porometry have also been used.

The water-balance method was used by Garcia Petillo and Castel (2007) in southern Uruguay (34° 39′ S 56° 46′ W; alt. 30 m), in a three-year-period, to measure the actual water use (*ET*) by mature orange trees (*C. sinensis* cv. Valencia) grafted on to trifolia rootstock (*C. trifoliata*). In a carefully monitored trial, annual water use averaged 767 mm from drip-irrigated trees and 620 mm from rain-fed trees (spaced 6 × 4 m, 416 trees ha^{-1}; crop cover increased from 30 to 50% during the course of the experiment). Seasonal potential evapotranspiration rates (ET_c) increased from 1.3 mm d^{-1} in the winter to 2.8 mm d^{-1} (spring) to 3.0 mm d^{-1} (summer) before declining in the autumn (1.0 mm d^{-1}). Peak ET_c rates occurred in December (3.3 mm d^{-1} or 80 L tree^{-1} d^{-1}). These values are similar to those recorded in Florida, Valencia (Spain) and in less arid areas of Israel, but less than those reported from Texas, Arizona, South Africa and Iran (see Table 3, Garcia Petillo and Castel, 2007), where reference-crop evapotranspiration rates (ET_o) were estimated from a USWB Class A evaporation pan with an appropriate pan factor (Allen *et al*., 1998). The average annual value of the crop coefficient ($K_c = ET_c/ET_o$) for the irrigated trees was 0.69. K_c varied with the season, with a minimum value in the summer (0.60), intermediate values in the spring and autumn (0.80 and 0.77 respectively) and a maximum in the winter (0.87). There was some evidence that in months when ET_o was large (January), ET_c rates were limited by stomatal control and K_c was reduced to 0.51.

In southern Brazil (22° 42′ S 47° 30′ W; alt. 546 m), Marin and Angelocci (2011) monitored the water use of seven-year-old irrigated (with under-tree micro-sprinklers) acid lime trees (*C. latifolia*, grafted on to *C. limonia* rootstock) over a (dry) winter and a (wet) summer season. Evapotranspiration (ET_c) from the orchard (tree spacing 7 × 8 m, 178 trees ha^{-1}), which included inter-row vegetation, was measured using the aerodynamic method, and transpiration (*T*) from individual trees (4.5 m tall; leaf area index = 5) by the sap-flow technique. Reference-crop evapotranspiration (ET_o) was computed using the Allen *et al*. (1998) version of the Penman–Monteith equation. In the winter, ET_c averaged about 0.6 mm d^{-1} and in the summer about 2.5 mm d^{-1} (range 1.0 to 4.6 mm d^{-1}). By comparison, ET_o averaged about 2.5 mm d^{-1} in the winter and 4.5 mm d^{-1} in the summer (range 1.3 to 6.5 mm d^{-1}). The corresponding values of the crop coefficient ($K_c = ET_c/ET_o$) were 0.24±0.12 (winter) and 0.65±0.11 (summer). Because the inter-row vegetation was dry, ET_c and T had similar low values during the winter. In the summer, as a result of the sensitivity of the stomata to the dryness of the air, the baseline coefficient ($K_{cb} = T/ET_o$) varied with the potential evaporation rate. Thus, when $ET_o < 3$ mm d^{-1}, $K_{cb} = 0.46 \pm 0.09$, and when $ET_o = 5.0$–6.5 mm d^{-1}, $K_{cb} = 0.34 \pm 0.06$. This reduction of K_{cb} with increase in ET_o demonstrates the close coupling of citrus trees to the atmosphere. Again in Brazil, Filho *et al.* (2005) had previously compared the stem heat-balance method for measuring sap flow (in young, acid lime plants) with transpiration measured with a weighing lysimeter and with a porometer. Agreement between the three methods was good, particularly over 24 h intervals, providing attention was given to possible sources of error. (The problems associated with the use of the heat-dissipation method for continuous measurement of sap flow in containerised nursery plants, as an aid to irrigation management, have been highlighted by Girardi *et al.* (2010)).

A similar comparison of ways of estimating actual water use in a drip-irrigated citrus (clementine) orchard (*Citrus reticulata*) in the semi-arid climate of southern Italy (40º 58′ N 17º 8′ E) was reported by Rana *et al.* (2005). Transpiration (T) was measured using the sap-flow technique, with the estimates of T carefully scaled up from a branch to a tree to an orchard, and evapotranspiration (ET) with the eddy-covariance method. Agreement between the two methods, over a 12-month period, was good. A Penman–Monteith-type model for predicting evapotranspiration from a clementine orchard in a Mediterranean climate was calibrated and successfully evaluated. Evapotranspiration rates reached 6–8 mm d^{-1} in mid-summer. The value of the crop coefficient (K_c) was found to vary between 0.8 and 1.2, depending on the growth stage. The high K_c value occurred during spring and early summer (coinciding with bud burst and flowering). By comparison, for the same conditions, Allen *et al.* (1998) suggest that K_c has a constant value of 0.75.

Rather different values of K_c were obtained by Villalobos *et al.* (2009) in Spain (37º 13′ N 6º 8′ W; alt. 52 m). Evapotranspiration (ET) was measured in a large, drip-irrigated plantation of mature clementine mandarin trees (spacing 6 × 5 m, 333 trees ha^{-1}) using the eddy-covariance method, whilst evaporation (E) from the bare soil surface was measured using micro-lysimeters. Transpiration (T) was found by the difference between ET and E. The leaf area index was 2.2. Measurements were made during two separate months, August and the following May, when ET averaged 2.6 and 2.1 mm d^{-1}, respectively. The corresponding K_c values were 0.44 and 0.43 and the baseline coefficients ($K_{cb} = T/ET_o$) were 0.30 and 0.25. After calibrating a derived model, a linear relationship (slope = 0.7) was found between T/ET_o and ground cover.

At a commercial level, a comparison of actual measured quantity of (supplementary) irrigation water applied by citrus growers in the Southwest Florida Water Management District (SFWMD) throughout the period 1994 to 2005 with the theoretical requirement was reported by Romero *et al.* (2009). Water balances were calculated based on estimates of ET_o (short grass, Penman equation) derived from data collected at two meteorological stations, and rainfall recorded at 50 sites across the three counties covered. Two sets of locally derived monthly K_c values, ranging from 0.70 to 1.05, were compared, and also two assumptions were made concerning the wetted area under the trees (40% or 60%). The conclusion was that actual water applications (average annual range 240 mm, wet year, to 410 mm, dry year, including cold/frost protection) were within the SFWMD permitted levels (300–560 mm, which excluded irrigation for cold protection), and that the simulated estimates were generally less than the values for individual districts, which in turn were reasonable. Similarly, Wheaton *et al.* (2006) used a water-balance approach to simulate the effects of a selection of variables, in particular the 'allowable' depletion of available water at different growth stages, on the annual irrigation requirements of a Hamlin orange orchard (*C. sinensis* grafted on to Carrizo citrange rootstock) planted on a free draining sandy soil in Lake County, Florida.

In their FAO reference manual, Allen *et al.* (1998) allowed for the effects of stomatal closure on transpiration rates when potential evaporation rates were high, by reducing the value of K_c in mid-season from 0.75 to 0.70 (for an orchard with 70% crop cover). When considering humid and subhumid climates they suggested that the K_c values listed should be increased by 0.1–0.2.

Summary: crop water requirements

1. It is not easy to quantify the water requirements of an orchard crop like citrus or to compare the results of measurements taken under different conditions and with different methods.
2. However, it appears to be accepted that low stomatal/canopy conductance restricts water use of *Citrus* spp. compared with other crops (Shalhevet and Levy, 1990, p. 967).
3. Recently reported research, summarised in Table 4.1, indicates that potential water use (ET_c) by mature orange trees in the subtropics ranges from 1.0 (autumn) to 3.0 mm d^{-1} (summer, maximum ET_c = 3.3 mm d^{-1}, which is equivalent to 80 L $tree^{-1}$ d^{-1}). The corresponding K_c values are 0.77 (autumn) and 0.60 (summer).
4. For seven-year-old lime trees in Brazil, ET_c (summer) = 2.5 mm d^{-1} ($K_c = 0.65$? this may be an error) and ET_c (winter) = 0.6 mm d^{-1} ($K_c = 0.24$, a low value due to dry inter-row vegetation).
5. In contrast, ET_c rates for clementine reached 6–8 mm d^{-1} in Italy with a correspondingly high crop coefficient (up to 1.2). In Spain, the *equivalent* K_c values were much lower at *c*. 0.4.
6. For comparison, Kriedemann and Barrs (1981, p. 398) had earlier cited values for (the equivalent of) $K_c = 0.7$ (summer) and 0.6 (autumn) in south Australia, as well as seasonal K_c mean values of 0.83 (in Arizona) and 0.68 (in Israel).
7. Similarly, Shalhevet and Levy (1990, p. 968) cited ET_c/ET_{pan} ratios in Arizona of 0.40 (winter) and 0.62 (summer), with ET_c reaching 5.2 mm d^{-1}.

Table 4.1 Crop water requirements: summary table showing the results of four experiments. ET_o is the reference crop evapotranspiration, ET_c is the potential evapotranspiration from a citrus orchard and K_c is the crop coefficient ($K_c = ET_c/ET_o$). T is transpiration. '?' means value uncertain. Evaporation units are mm d^{-1}

	Spring	Summer	Autumn	Winter
Uruguay (orange)[a]				
ET_o	3.5	5.0	1.3	1.5
ET_c	2.8	3.0	1.0	1.3
K_c	*0.80*	*0.60*	*0.77*	*0.87*
Brazil (lime)[b]				
ET_o		4.5		2.5
ET_c		2.5		0.6
K_c		*0.65?*		*0.24*
Italy (clementine)[c]				
ET_c		6-8		
K_c	*1.0–1.2*	*up to 1.2*	*0.8*	
Spain (clementine)[d]				
ET_c	2.1		2.6	
*K*c	*0.43*		*0.44*	
T/ET_o	0.25		0.30	

[a] Garcia Petillo and Castel (2007); [b] Marin and Angelocci (2011); [c] Rana *et al.* (2005); [d] Villalobos *et al.* (2009)

8. For immature trees, the recommendation in Israel was to apply 10, 15, 25, 45, 65 L $tree^{-1}$ day^{-1} during mid-summer in years one to six after planting respectively, and afterwards 100 L $tree^{-1}$ day^{-1}, which is equivalent to 4–4.5 mm day^{-1} (Shalhevet and Levy, 1990 p.968).
9. Given the variability in some of the results reported, and until more is known about citrus water requirements, the approach proposed by Allen *et al.* (1998) seems reasonable.

Water productivity

The role that so-called 'deficit irrigation' (the application of water below ET_{max} levels) can play in improving the water productivity of field crops has been reviewed by Fereres and Soriano (2006). In particular they emphasised how 'regulated' deficit irrigation can increase farm profits, particularly in fruit trees and vines. With *Citrus* spp., it has become a popular area of study and a large number of experiments have been reported in which the aim was to identify at what stages in the development of the crop water applications can be reduced below the maximum without a proportional loss in marketable yields (this assumes that there are yield-determining processes that are differentially sensitive to water deficits). As Fereres and Soriano (2006) stated, research linking the physiological basis of these responses (generally well understood for

Citrus spp.) to the design of practical ‘regulated deficit irrigation strategies’ could have a significant impact in water-limited areas (or where it is expensive to deliver water to the field). A tall, aerodynamically rough crop like citrus is also better coupled to the atmosphere than a short field crop, so that a decline in stomatal conductance will be translated into a corresponding reduction in transpiration (and to a lesser extent photosynthesis). The results of some of these experiments are considered in the order orange, lemon and lime, and clementine.

Orange

In south-east Spain (37º 45′ N 0º 38′ W; alt. 30 m), Pérez-Pérez *et al.* (2008a; 2008b) compared the responses of two popular drought-tolerant rootstocks (Cleopatra mandarin (*C. reshni*) and Carrizo orange (*C. sinensis* × *Poncirus trifoliata*) with a common eight-year-old sweet orange scion (Love late, *C. sinensis*) to deficit irrigation over three seasons. At this (previously irrigated) site, the average annual (winter) rainfall is 283 mm and reference crop evapotranspiration, ET_o, is 1238 mm). Water was withheld at two stages of fruit growth (during phase 1, cell division, and during phase 3, ripening), but fully irrigated during phase 2, cell expansion. The control treatment was fully irrigated throughout fruit growth. In all the attributes of drought tolerance tested (water uptake, xylem water potential at midday, CO_2 assimilation and vegetative growth) ‘Cleopatra’ out-performed ‘Carrizo’ when the deficit treatment was applied. However, despite these indicators, deficit irrigation reduced yields from both rootstocks, when averaged over the three seasons, by similar amounts, from 45.0 to 42.2 kg tree^{-1} for ‘Carrizo’ and from 38.8 to 35.9 kg tree^{-1} for ‘Cleopatra’ compared with the control (plant density = 833 trees ha^{-1}). Deficit irrigation increased the water-use efficiencies (based on irrigation applied) from 6.4 (for the fully irrigated control treatment) to 8.6 kg m^{-3} for ‘Carrizo’ and from 5.6 to 7.2 kg m^{-3} for ‘Cleopatra’. The authors recommended both rootstocks for use in semi-arid areas. The results of this experiment were afterwards subjected to an economic analysis (Pérez-Pérez *et al.* 2010). After making realistic assumptions about costs of production on a typical 10 ha orchard in the Murcia region of south-eastern Spain, deficit irrigation was shown to be profitable for both rootstocks, especially when the price of water was high. The Carrizo rootstock was more profitable than Cleopatra.

In a similar experiment at the same site in south-eastern Spain, Pérez-Pérez *et al.* (2009a) investigated during two seasons the influence of deficit irrigation during phase 3 (maturation to harvest) of fruit development in a late-maturing variety of sweet orange, Lane late (*C. sinensis*) grafted on to Carrizo citrange rootstock. Although the results were influenced by winter rainfall, the main effects of withholding irrigation during phase 3 (1 October to 1 March) were to increase the total soluble solids (TSS) and titratable acids (TA) without influencing the maturity index (TSS/TA ratio) thereby allowing harvesting to be delayed, a requirement of the international fresh fruit market.

In southern Uruguay (34º 39′ S 56º 46′ W; alt. 30 m), Garcia Petillo and Castel (2004) undertook a similar study in an area of relatively high rainfall (the average rainfall over the five years of the experiment was 1174 mm, range 796–1362 mm). In a comparison of five daily drip-irrigated treatments (Valencia orange grafted on to *Poncirus trifoliata*), the largest yield (five-year average 36.7 t ha^{-1}) of export-quality fruit (diameter >69 mm) was obtained from the treatment in which the evapotranspiration (ET_c, based on Allen *et al.*, 1998) loss was replaced 100% (average annual application 262 mm). This yield compared with 19.2 t ha^{-1} from the unirrigated control and 31.6 t ha^{-1} from the treatment in which only 50% ET_c was applied (152 mm). Applying 50% excess water (150% ET_c, 405 mm) increased the tree size, but did not increase fruit yield. Withholding irrigation for two months (180 mm) during phase 2 of fruit growth (expansion) reduced yields by 22% to 28.6 t ha^{-1} compared with the fully irrigated treatment. The corresponding irrigation water-use efficiencies were 6.7 (100% ET_c), 3.4 (50% ET_c) and 4.5 kg m^{-3} (water withheld). In this case, deficit irrigation did not increase water-use efficiencies.

Long-term effects (nine years) of supplementary irrigation on the yield of Navel oranges (*C. sinensis* cv. Spring on *Poncirus trifoliata* cv. Rubidoux rootstock) were studied in an experiment in north-west Uruguay (32º S 58º W; average annual rainfall 1300 mm). Irrigation (with micro-sprinklers) was beneficial during fruit growth phases 1 (beginning from bud swelling) and 2 and, in some years, phase 3 by increasing the final (marketable) fruit size (Figure 4.6). It also attenuated biennial bearing and led to cumulative yield increases with time. Satsuma mandarin cv. 'Owari' responded in similar ways to Navel orange (Goñi and Otero, 2011).

Figure 4.6 Irrigation can increase the marketable size of citrus fruit – Botswana (HDT). See also colour plates section.

In another regulated deficit irrigation experiment, this time in south-west Spain (37° 44′ N 5° 12′ W) with mature orange trees (cv. Salustiana) grafted on to Carrizo citrange rootstocks, differential irrigation treatments (0.75, 0.65 and 0.50 times the full water requirement) were applied from early June to mid-October. Yields of fresh fruit from all three treatments (average *c*. 100 kg tree^{-1} during the three years of the experiment) were similar to those from the well-watered control (100% $\times\ ET_c = 0.7 \times ET_o$, with an average annual application of 515 mm). The principal beneficial effect of deficit irrigation was to improve the quality of the fruit by increasing the TSS, TA and peel thickness. Irrigation water productivity was increased from 0.15 (control) to 0.25 (50% replacement) kg fruit tree^{-1} mm^{-1} (averaged over three years). At a planting density of 416 trees ha^{-1}, these are equivalent to 6.2 and 10.4 kg m^{-3}, respectively. The midday stem water potential was rarely less than −1.2 MPa in any of the treatments. The soil was a sandy clay loam with an effective depth of 0.6 m, although roots went deeper (García-Tejero *et al*., 2010a). The results of the same experiment were reported again by García-Tejero *et al*. (2011c), but this time yields from four years (2004–2008), rather than three, were included. A linear relationship was presented between the four-year average irrigation water productivity (range 0.11 to 0.34 kg fruit tree^{-1} mm^{-1}, or 4.5–14 kg m^{-3}) and the average annual depth of water applied (range 700 to 340 mm).

A similar experiment was described by García-Tejero *et al*. (2010b). Deficit irrigation (45% less water applied compared with the well-watered control) during: (1) the flowering phase reduced the number of fruit from 600 to 500 tree^{-1}, (2) the fruit expansion phase reduced the size of the fruit from 270 to 210 g fruit^{-1} and (3) the fruit maturation phase affected certain quality parameters, including increases in the TSS and TA. The response was greatest in the second year of the experiment.

The same team of authors also reported the results of a group of three similar experiments (sweet oranges cvs. Salustiana and Navaelina, both grafted on to Carrizo citrange rootstocks) conducted in the same locality, the Guadalquivir river basin in south-west Spain (García-Tejero *et al*., 2011a). These findings confirmed the water savings that were possible (*c*. 100–130 mm, 20–30%), through carefully programmed deficit irrigation, without loss in fruit yield. Irrigation water-use efficiencies ranged between 7 and 12 kg m^{-3}, and averaging 9 kg m^{-3} across all 12 treatment combinations.

Yet another similar experiment from south-west Spain was reported by Muriel *et al*. (2011). A regulated deficit treatment (60% replacement) was compared with a control (100% replacement) and with another deficit treatment based on shoot water-potential measurements (how is not specified). A weakness in the methodology described is the empirical way in which the quantity of water to apply to 10-year old orange trees (*C. sinensis* cv. Navelina on Carrizo citrange: 416 trees ha^{-1}) was calculated:

$$\text{Water applied} = [\Sigma ET_o \times K_c \times K_r - \text{rain}]$$

where ET_o is the reference crop evapotranspiration (Penman–Monteith), K_c is a crop factor (0.55), K_r is a ‘reduction coefficient’ (0.7, it is not clear what K_r represents); rain = effective rain (0.7 × actual rain). Presumably this calculation gave the depth of water to apply to the control treatment and the regulated deficit treatment was 60% of this arbitrary value (60% of what? – this is the fundamental question). After one year, there was no difference in irrigation water productivity between these two treatments, both averaging about 2.5 kg fresh fruit m^{-3}.

In New South Wales, Australia, Treeby *et al.* (2007) monitored the effects of deficit irrigation on the yield and quality of fruit from Bellamy Navel orange grown on five rootstocks during two seasons. Applying half the quantity of water at each irrigation event on both sides of the tree, or applying half the quantity of water alternatively either side of the tree, resulted in a larger number of small fruit compared with the well-irrigated control, although the total fruit yield was the same. Both deficit irrigation treatments increased the TSS and the titratable acid content of the fruit due to passive concentration. The incidence of albedo breakdown (folding of the outer coloured portion of the rind) was reduced, but the degree of reduction varied considerably between rootstocks, being greatest for sweet orange and least for Carrizo citrange. There is therefore a trade-off between the number of fruit suitable for the fresh market in terms of (improved) rind quality (depending on rootstock) and (reduced) fruit size. Again in New South Wales, Hutton *et al.* (2007) showed that, although shoot growth was reduced by extending the interval between irrigations from 3 to 17 days during fruit growth stages 2 and 3, fruit yield was unaffected, despite a marginal reduction in fruit size, and irrigation water productivity was increased.

In Florida, mechanical harvesting of citrus fruit by shaking the tree is expected to increase as labour costs increase. At the same time, industry wants the current harvesting period to be extended (beyond March). If harvest is delayed to May/June, late-season cultivars like Valencia will have immature green fruit (for harvesting next year) on the tree at the same time as mature fruit (for harvesting in the current year). Delaying harvest would mean that, with non-selective mechanical harvesting, immature fruit would be removed from the tree as well as mature fruit, prejudicing next year's crop. By artificially imposing water stress during the winter (from December to February/March), Melgar *et al.* (2010) were able to delay flowering by two to four weeks. As a result, the immature fruit were still small enough in June (*c.* 25 mm diameter) to remain on the tree without a loss in yield (or quality) in either year. It is not known how water stress would be imposed in an orchard on a large scale.

Lemon and lime

The responses of 20-year old Verna lemon trees (*C. limonium*, grafted on to a sour orange rootstock; spacing 6 × 6 m, 278 trees ha^{-1}) to a selection of fixed-interval irrigation regimes (from 4 to 12 applications per year at 85 mm per application), compared with a daily drip-irrigated treatment, were recorded in Murcia, Spain for three years (Sánchez Blanco *et al.*, 1989). The drip-irrigated crop consistently out-yielded the other treatments (205 kg $tree^{-1}$ compared with 174 kg $tree^{-1}$ from the best flood irrigated crop, monthly applications, and 68 kg $tree^{-1}$ from the driest treatment). The effects on fruit quality were largely inconsistent, except that frequent irrigation tended to increase fruit size. The results of this experiment (as presented) have limited generic value.

In São Paulo State, Brazil (22º 42′ S 47º 49′ W; alt. 511 m), a weighing lysimeter was used to measure the actual water use (*ET*) of young (one to four years old) Tahiti acid lime trees (*C. latifolia*) grafted on to Swingle citrumelo rootstocks. Differential irrigation was applied with drip irrigation at 0.25, 0.50, 0.75 and 1.0 × ET_c. Yields were recorded over a two-year period. All four irrigated treatments out-yielded the unirrigated control (by an average of 21 kg tree^{-1} in 2004 and by 10 kg tree^{-1} in 2005) but, because of tree-to-tree variability, yield differences between the irrigated treatments were not consistently significant (coefficient of variation 32% and 24% respectively). There was no effect of irrigation on fruit quality (Alves *et al*., 2011). There are probably opportunities to analyse the data in more detail.

Clementine

In eastern Spain, Ballester *et al*. (2011) sought to justify the recommendation to growers that deficit irrigation was a practical means of saving water. In a field experiment (*C. clementina*, cv. Clementin de Nules, 8 to 10 years old) two deficit irrigation treatments were compared with a fully (daily) drip-irrigated control over three seasons (average annual ET_o = 1070 mm, Penman–Monteith; rainfall = 450 mm). In the mild deficit treatment, water was withheld from the end of the physiological fruit drop (mid-July) for up to 69 days, whilst keeping the midday stem water potential above −1.3 to −1.5 MPa, a previously determined threshold value for avoiding fruit size reduction. In the severe deficit treatment the threshold value was taken to be −1.5 to −1.7 MPa. Averaged over the three years, there was a 15% water saving in the mild deficit treatment (309 mm compared with 364 mm) and an 18% saving in the severe one (298 mm). Because of compensatory growth that occurred when full irrigation was re-introduced at the end of the mild deficit period (for three months before harvest), average yields (41 t ha^{-1}) and fruit size were similar to those of the control treatment (42 t ha^{-1}), whilst other aspects of fruit quality were even improved, and vegetative growth was reduced. The severe deficit treatment reduced yields (36 t ha^{-1}). The mild deficit strategy was therefore recommended to growers as a commercially worthwhile management system.

Again in Spain (30º 30′ N 0º 24′ E), drought during the periods of flowering and early fruit set reduced yields from the same variety of clementine. This was a result of fewer fruit reaching maturity. Water stress later in the season reduced the size of the fruit and aspects of quality, including an increase in skin thickness, TSS and acid content (Ginestar and Castel, 1996). However, following Doorenbos and Kassam (1979), when yields for the two years of the experiment ($n = 6 \times 2$) were expressed as the relative yield reduction, and plotted against the corresponding relative evapotranspiration deficit, there was a common linear function (despite considerable yield differences between the two years) with a slope of 2.0 (the yield response factor, K_y). This value suggests extreme sensitivity to water stress, regardless of the stage of growth.

In a subsequent experiment conducted in the same 10-year-old, drip-irrigated orchard, a selection of regulated deficit irrigation treatments were compared, again only over a two-year period, at three different growth stages, corresponding to spring, summer and autumn (González-Altozano and Castel, 1999; 2000). As with similar experiments referred to above, applying 75% or 50% less water than was needed in the spring reduced fruit yields by 60% and 28%, respectively (fewer fruit). Modest savings in water in the summer period (7–14%) had no effect on yield or quality relative to the control, well-irrigated treatment, (due partly to compensatory growth on re-watering) providing that the pre-dawn leaf water potential did not fall below -1.3 MPa. Deficit irrigation in the autumn reduced fruit size and quality (and value), and was not recommended. Applying only 44% of the water requirement (as determined by a weighing lysimeter) throughout the year only reduced yields by 17% (smaller fruit), but increased TSS and acids in the juice without affecting the maturity index or creasing of the skin. The water-use efficiencies (yield divided by irrigation + rainfall) of this treatment averaged about 4.0 kg m^{-3} compared with 3.3 kg m^{-3} for the control. The corresponding values for the two summer deficit treatments (considered by the authors to be the best time to apply deficit irrigation) were similar to the control at 3.4 and 3.7 kg m^{-3}. As with many of these experiments, long-term treatment effects, important for tree crops, are not reported.

In the Western Cape region of South Africa (34º S 19º E; alt. 100 m), tensiometers were used to decide when to irrigate and how much water to apply to six-year-old Mihowase satsuma mandarin trees (*C. unshiu* grafted on to Troyer citrange rootstock) during the period beginning one to four weeks after the ‘December fruit drop’ up to the first selective harvest. Irrigation before the soil water potential was less than -60 kPa at a depth of 0.60 m maintained yields at levels achieved with more frequent irrigation applications of smaller quantities of water (soil profile returned to field capacity at each irrigation event) on both the soils tested (sandy–loam and clay–loam), whilst increasing the TSS content, the desired goal (Peng and Rabe, 1998).

Table 4.2 Summary of irrigation water productivity values from a selection of ‘deficit’ irrigation experiments with *Citrus* spp. Control is 100% replacement of *ET*. Deficit shows percentage replacement, where given.

	Irrigation water productivity (kg fresh fruit m^{-3})		
	Control (100% *ET*)	Deficit	Reference
SE Spain: orange	6.4	5.6–8.6	Pérez-Pérez *et al.* (2008a; 2008b)
S. Uruguay: orange	6.7	3.4(50%)–4.5	Garcia Petillo and Castel (2004)
SW Spain: orange	6.2	10.4(50%)	García-Tejero *et al.* (2010a; 2011c)
	4.5	14(50%)	
SW Spain: orange		7–12	García-Tejero *et al.* (2011a)
SW Spain: orange	2.5	2.5(60%)	Muriel *et al.* (2011).
E Spain: clementine	11.5	10.5–12.1	Ballester *et al.* (2011)
Spain: clementine	3.3[a]	3.4–4.0[a]	González-Altozano and Castel (1999; 2000)

[a] Rainfall plus irrigation

Table 4.2 summarises the irrigation water-use efficiency values given in the text above. There is no consistent convincing evidence that deficit irrigation leads to higher water productivities. For 100% replacement, the water-use efficiency for fresh oranges is probably in the region of 6–7 kg m^{-3}. The comparable partial replacement of *ET* values range from 3–14 kg m^{-3}. Complications arise as a result of the timing of the deficit treatments in relation to the phase of fruit growth, and the ways in which *ET* is determined. Is the deficit treatment a percentage of a realistic ET_c value?

By contrast, in a detailed report of a five-year drip irrigation experiment in New South Wales, Australia (34º 36′ S 146º 25′ E; alt.136 m), 'partial root-zone drying' increased the water-use efficiency of mature Navel orange trees (*C. sinensis*). This technique allowed the clay–loam soil to dry out on one side of the tree, whilst keeping the other side wet. After four weeks the positions were reversed. By so doing the average amount of water applied annually was about 40% less than that applied in the conventional drip treatment (290 mm cf. 480 mm). As there was only a small reduction in yield (−9%), water-use efficiency was increased. However, since both fruit size and juice percentage were reduced, the technique was considered to be most appropriate for the production of fruit juice. Supporting measurements confirmed the belief that the fully hydrated roots in the wet portion of the root zone maintained a favourable plant water status (allowing plant development to continue as normal), whilst a chemical signal (e.g abscisic acid), originating in the dried roots, induced stomatal regulation of transpiration, thereby conserving water. Stomatal conductance was at its maximum from daybreak to approximately 0900 h after which conductance declined to very low levels by midday, (in response to an increase in the saturation deficit of the air, range 1–8 kPa) where it remained for the rest of the day (Hutton and Loveys, 2011).

Summary: water productivity

1. A number of similar deficit irrigation experiments have been reported, mainly with orange (but on different rootstocks), and predominantly in Spain and Uruguay.
2. There is no clear evidence to show that deficit irrigation increases water productivity, but indications that 'partial root-zone drying' might, given appropriate circumstances.
3. For fully irrigated crops, the yield responses to water applied are in the range 6–7 kg fresh fruit m^{-3}, and for partially irrigated crops they are between 3 and 14 kg m^{-3}. These values compare with the estimate by Doorenbos and Kassam (1979) of between 2 and 5 kg fresh fruit m^{-3}.
4. As there are problems in defining how much water to apply, even in the 100% replacement treatments, it is not always clear which comparisons are valid.
5. Many experiments were of limited duration so, with one or two exceptions, it was not possible for the cumulative benefits to be assessed.

6. There is no consensus view on the degree of deficit irrigation and its timing that is likely to benefit farmers, nor of its value in terms of water saving and improvements in water-use efficiency. When is it financially worthwhile?
7. Withholding irrigation during phase 1 of fruit growth reduces the number of fruit reaching maturity.
8. Withholding irrigation during phase 2 of fruit growth reduces fruit size, but applying full irrigation afterwards results in compensatory growth and a similar final fruit size.
9. Withholding irrigation during phase 3 of fruit growth increases TSS and TA contents of the fruit, but without influencing the TSS/TA ratio, thereby allowing harvesting to be delayed. Skin thickness is also increased. Deficit irrigation may also reduce albedo breakdown of the rind. Fruit size may be reduced.
10. 'Partial root-zone drying' increases the water-use efficiency of mature Navel orange trees.
11. Water stress in the winter delays flowering, thus facilitating mechanical harvesting.
12. To avoid fruit size reduction, the midday stem water potential should not be less than −1.3 MPa.
13. Fruit yield is influenced by the plant water status level in the previous year, as well as by water status in the current year (Doorenbos and Kassam, 1979).
14. Changes in fruit quality can be seen in one season, whereas yield is cumulative and slow to develop (Shalhevet and Levy, 1990).
15. Water availability influences the following aspects of fruit quality: physical attributes such as fruit size, peel thickness, colour, juice content; chemical factors including acid and sugar contents; and minor constituents that influence palatability (Shalhevet and Levy, 1990).

Irrigation systems

Citrus orchards can be irrigated in many different ways. For example, in Florida, solid-set sprinkler systems, rainguns, flood (Figure 4.7) and subsurface methods have all been used. It was in the 1980s that micro-irrigation systems became popular, not only in new plantings, but also in existing orchards where micro-irrigation displaced other methods, particularly rainguns (Smajstria, 1993). The term 'micro-irrigation' is used to describe irrigation systems that use low flow-rate emitting devices (emitters) that place the water on (or just below) the soil surface close to the plant. These systems are characterised by the use of small diameter, polyethylene lateral pipes, with low flow rates at each emitter, and operated at low pressures. Specific types of micro-irrigation systems include drip (trickle, Figure 4.8) and micro-sprinklers (under-tree, Figure 4.9). These systems allow small quantities of water to be applied at frequent intervals, usually to only part of the root zone. In Swaziland, largely because of the opportunities it offers for labour saving, water saving and power saving, micro-irrigation (particularly drip) has replaced under-tree drag-line sprinkler systems (Pyle, 1985). In areas prone to frosts (e.g. Florida), micro-sprinklers can also provide some protection against frost damage to young trees (Rieger *et al.*, 1986).

Figure 4.7 Newly planted citrus orchard in southern California with border-strip flood irrigation (MKVC). See also colour plates section.

Figure 4.8 Drip irrigated citrus. Note the small area of wetted soil surface – California (MKVC).

Figure 4.9 Mature citrus orchard in southern California irrigated with micro-sprinklers (MKVC).

Irrigation scheduling

Many different approaches to scheduling irrigation (timing and amount of water to apply) in citrus orchards have been advocated, but how widely any of them have been or are used commercially by growers is uncertain. These schedules are based on measurements of plant water status, such as fruit expansion, stomatal opening, trunk diameter, leaf/stem water potential and/or soil water status (content or water potential), and/or estimates of the soil water deficit based on calculated evapotranspiration rates (Shalhevet and Levy, 1990). For example, Snyder and Meyer (1992) and Ramsey (2007) describe, and recommend, the use of the water-balance approach for citrus growers in California and Australia, respectively, whilst, in Florida, Morgan *et al.* (2009) are promoting a web-based water-balance Citrus Irrigation Scheduler. However, unfortunately, many of these methods are too complex to be used routinely by farmers without assistance. This view is supported by the results of a detailed survey by Stevens (2007) in South Africa. He found that only 18% of irrigation farmers (including citrus growers) make use of an objective irrigation scheduling method. The rest rely on subjective criteria such as intuition, observation, local knowledge and experience. Different perceptions of the concept of 'irrigation scheduling' led, in part, to a communications gap between scientists and farmers.

Despite the limited uptake of objective scientific method, the research continues. A few publications describing recent developments in irrigation scheduling techniques for citrus are summarised below.

In São Paulo Sate, Brazil, Da Silva *et al.* (2005) used physiological criteria to identify when to irrigate 'Tahiti' acid lime trees (*C. latifolia*) on 'Swingle' citrumelo rootstocks. By allowing the (clay) soil to dry for 40 days, and comparing the values relative to those from well-irrigated (drip) trees, they identified the threshold depletion levels of available water in *c*. 1.0 m soil depth (total 125 mm m^{-1}). Actual evapotranspiration, determined with a weighing lysimeter, was restricted when the degree of depletion reached 57%. By contrast, stomatal conductance, photosynthesis, transpiration and leaf water potential all declined at 40% depletion, which corresponded to a pre-dawn leaf water potential measurement of −0.62 MPa.

The value of several plant water-status-based indicators in deciding when to irrigate Satsuma mandarin trees (*C. unshiu*) was determined in South Africa (33º 56′ S 18º 52′ E; alt.157 m) by Dzikiti *et al.* (2010). Midday leaf water potential measurements (made on young potted trees) were considered to be too variable (range of fluctuation 2.0 MPa) because of stomatal oscillation (the severity of which increased when the saturation deficit of the air reached *c*. 3 kPa). Oscillations are a characteristic of most *Citrus* species. By comparison, midday stem water potential measurements were more representative of tree water status (corresponding range *c*. 0.3 MPa). In contrast, pre-dawn leaf water potential measurements, although not affected by oscillations, were not sufficiently sensitive to register mild water stress. No statistically valid relationship was found between canopy reflectance and the water status of mature trees, and there was only limited success with young trees and then only when they were experiencing severe water stress.

On their own, remotely sensed spectral data were therefore unlikely to be of value for scheduling irrigation of *Citrus* orchards. Subsequent studies by Dzikiti *et al.* (2011) at the same location, however, suggested that, as reflectance was an indicator of the relative changes in the contribution of internally stored water to daily transpiration (up to 25% in mature Midnight Valencia orange trees), changes in canopy reflectance, in selective wavelength bands, could (potentially) be used for irrigation scheduling. This response was despite seasonal variation in reflectance (from 15% in the winter to 22% in the summer) associated in part with changes in tree phenology.

The use of stem shrinkage measurements to schedule irrigation was evaluated in Spain (39º 30′ N 0º 24′ E; alt. 68 m), in an orchard planted with Clementina de Nules (*C. clemantina*) grafted on to Carrizo citrange (*C. sinensis*), by Velez *et al.* (2007). The aim was to ensure that the maximum daily trunk shrinkage did not exceed 125% of the value for the well-watered control tree during the three months following the 'June drop'. In practice, this requirement also meant that the midday stem water potential did not fall below −1.3 MPa, a previously determined threshold value. In the two years the experiment ran, the deficit irrigation treatment resulted in seasonal water savings of 87 mm and 43 mm, equivalent to 18% and 12%, respectively, of the total water application (excluding rainfall) without any loss in yield, and without affecting fruit weight distribution. Variation in daily trunk shrinkage was best correlated with solar radiation (not mean daily air temperature, as originally reported). A minimum of six trees were needed to obtain reasonable mean values on which to base decisions on when to irrigate.

The results of a similar study in south-west Spain were reported by García-Tejero *et al.* (2011b). Measurements made during a season in a deficit irrigation experiment in

Figure 4.10 Harvesting densely planted citrus – Seville, Spain (EF). See also colour plates section.

a commercial orchard of sweet orange (cv. Nevelina) indicated how the difference in temperature between the crop canopy (T_c) and the ambient air (T_a) ($T_c - T_a$, range up to 6 °C) was a sensitive indicator of tree water status, as was the maximum daily stem shrinkage (range 130–300 μm). Since these variables were not only highly correlated with each other, but also with midday stem water potentials (range −0.5 to −2.8 MPa) and stomatal conductances (range 40–240 mmol m^{-2} s^{-1}), the authors were of the view that measurements of ($T_c - T_a$) with an infrared thermometer could be used to monitor crop water status and to schedule irrigation (Figure 4.10).

In Florida, Fares and Alva (2000) evaluated the use of capacitance probes for irrigation scheduling of three-year-old *Citrus* trees growing in fine sand. Capacitance probes were used to monitor continuously soil water content at different depths within and below the root zone, and allowable depletion levels were specified. Throughout most of the growing season the soil water content in the root zone was maintained within the limits specified. Capacitance probes are now being used in Florida with success.

Fertigation

Advances in micro-irrigation techniques (e.g. drip and under-tree sprinklers) have facilitated the adoption of fertigation (the application of nutrients through the irrigation system) of *Citrus*. The benefits of fertigation include the frequent delivery of nutrients in soluble form, together with water, directly into the root zone. Good irrigation management is necessary to minimise leaching of nutrients. In a detailed review of the topic, Alva *et al*. (2008) summarised the results of the limited number of long-term fertigation trials with *Citrus* (orange and grapefruit) in terms of growth responses of young trees, and yields and nutritional status of fruit-bearing trees. Some of the practical problems associated with this method of fertiliser application were also highlighted.

An advanced form of this method of irrigation was developed in Spain and has since been commercialised in several countries, including Australia, South Africa and the USA. Known as 'open hydroponics', *Citrus* trees are planted at a high density ($>$750 trees ha^{-1}) and irrigated (with drip) by short-duration, low-volume pulses throughout daylight hours with fertiliser injected into the water (except on rainy days). In this way, water and nutrients are readily available within the wetted soil volume, where a mat of roots develop (Falivene, 2005). After two years' commercial experience in Florida with what is called the 'Advanced Citrus Production System', the observed benefits included early production of high-quality fruit (at 24 months) with the opportunity to achieve potential yields when the trees mature. As there is a limited reserve of available water in the (restricted) root zone, especially in sandy soils, the system is vulnerable to breakdowns. Good management is essential. Looking to the future, there are opportunities to extend the system to very high-density citrus production under cover (Schumann, 2011).

Summary: irrigation systems

1. Many different methods of irrigation have been used to irrigate *Citrus*. Micro-sprinklers and drip are now the generally preferred systems, both of which can be used for fertigation.
2. Many different ways of scheduling irrigation have been advocated, but how many are used in practice is uncertain. Capacitance pobes are used in Florida.
3. Stem water potentials are related to the degree of stem shrinkage, which occurs when a tree experiences water stress.
4. A method of irrigation scheduling based on the degree of daily stem shrinkage has been evaluated. This practice has resulted in water savings of 12–18% compared with a well-watered control.
5. To ensure that water stress is not a yield-limiting factor, the midday stem water potential should not fall below -1.3 MPa.
6. The limiting soil water depletion ratio was estimated to be 0.4 during the period from flowering to fruit drop, and afterwards 0.6–0.7 (Doorenbos and Kassam, 1979).
7. On their own, remotely sensed spectral data are unlikely to be of value for scheduling irrigation of *Citrus* orchards.
8. An advanced form of fertigation known as 'open hydroponics' has been commercialised in several countries.

General conclusions

Citrus spp. originated in south-east Asia and are grown commercially, mainly in the subtropics, where irrigation is necessary, but where there is also great pressure to conserve water. Compared with most crops, research on *Citrus* is complicated by the complexity of its taxonomy and the diverse range of species and cultivars that are grown. This complexity is further complicated by the choice of rootstock. Drawing generic conclusions from the research reported is therefore not straightforward because of possible genotype/environment interactions. In summary, as a result of this review, our current state of knowledge of the water relations of citrus appears to be as follows:

1. The effects of water availability on vegetative growth are understood in general terms, but the relationships have not yet been quantified.
2. The need for a ‘rest period’ to induce flowering is understood, but its magnitude (in terms of a drought stress index or day-degrees) does not appear to have been specified with precision.
3. Similarly, the effects of drought on flower and fruit formation and retention is understood in general terms, but again the relationships have not been quantified in useful ways for specific cultivars.
4. Rooting depth and distribution have only been described in a limited number of situations. Much remains to be done to quantify root distribution in relation to soil water availability in order to compare the contribution of specific rootstocks to drought tolerance (for example).
5. Environmental factors influencing stomatal conductances are generally well described and relationships with some growth processes established.
6. Compared with other crops, low stomatal/canopy conductance restricts water use of *Citrus* spp. Some (limited) progress has been made in quantifying crop water requirements under specific conditions.
7. Despite many recent attempts to specify how little water can be applied at specific growth stages to optimise water productivity through regulated deficit irrigation, no consensus view has emerged. This dilemma may, in part, be due to the difficulty of quantifying actual crop water use and allowable soil water deficits.
8. The yield response to ‘full’ irrigation is of the order 6–7 kg fresh fruit m^{-3}, as a result of an increase in the number of fruit of marketable size. There are also improvements in fruit quality.
9. The most effective way of irrigating a citrus orchard is with a micro-irrigation system (drip or micro-sprinklers). Both methods require answers to the question: what proportion of the root zone needs to be irrigated? Both methods, especially drip, allow water to be applied (with fertigation) at frequent intervals (including several times a day – open hydroponics), although formal evidence of the benefits to be obtained from this level of intensification is lacking.

Summary

The results of research on the water relations and irrigation needs of *Citrus* spp. are collated and reviewed in an attempt to link fundamental studies on crop physiology to drought mitigation and irrigation practices. Background information is given on the centres of origin (South-east Asia) and of production of citrus (areas with subtropical Mediterranean-type climates). The effects of water stress on the development processes of the crop are summarised, followed by reviews of the plant–water relations, crop water requirements, water productivity and irrigation systems. The topic is complicated by the diversity of species and cultivars (including rootstocks) that are embraced within *Citrus* spp. The effects of water availability on vegetative growth are understood in general terms, but the relationships have not yet been quantified. Similarly, the need for a 'rest period' to induce flowering is understood, but its magnitude (in terms of a drought stress index or day-degrees) does not appear to have been specified with precision. Again, the effects of drought on flower and fruit formation and retention are understood in general terms, but again the relationships have not been quantified in useful ways for specific cultivars. Rooting depth and distribution have only been described in a limited number of situations. Environmental factors influencing stomatal conductances are generally well described, and relationships with some growth processes established. Compared with other crops, low stomatal/canopy conductance restricts water use of *Citrus* spp. Some (limited) progress has been made in quantifying crop water requirements in specific conditions. Despite many recent attempts to specify how little water can be applied at specific growth stages to optimise water productivity through regulated deficit irrigation, no consensus view has emerged. The yield response to 'full' irrigation is of the order of 6–7 kg fresh fruit m^{-3} as a result of an increase in the number of fruit of marketable size. There are also improvements in fruit quality. The most effective way of irrigating a citrus orchard is with a micro-irrigation system (drip or micro-sprinklers), but both methods require answers to the question: what proportion of the root zone needs to be irrigated? Both methods, especially drip, allow water to be applied (with fertigation) at very frequent intervals (including several times a day), although formal evidence of the benefits to be obtained from this level of intensification is lacking.

Endnote

1 For more detail see also Ribeiro *et al.* (2009).

5 Date palm

Introduction

The date palm (*Phoenix dactylifera*) is one of the oldest known fruit crops (Figure 5.1). It is subtropical in origin and cultivation. It may have originated in Mesopotamia (southern Iraq), where it has been cultivated for at least 5000 years. The subsequent spread of the date palm east through Iran to India and Pakistan, and west across North Africa to Spain, and its current distribution (dates were introduced from Spain to California in the seventeenth or eighteenth century) are well documented (e.g. Pareek, 1990; Chao and Krueger, 2007). The date palm not only provided a concentrated energy food, which could be easily stored and carried on long journeys across the deserts, but it also provided shade and protection from desert winds (Barreveld, 1993). Date palm is a crop best suited to hot, arid regions. It does not grow well in the wet tropics where rain prevents pollination and the palms are completely sterile (Purseglove, 1972). An old saying describes the date palm as 'growing with its feet in the water and its head in the fire', conditions found in the wadis and oases of West Asia.

Dates are now widely grown in the arid regions between latitudes 15º N and 35º N, and from Morocco in the west to India in the east. In 2010, according to FAOSTAT (2012), the leading five countries in terms of production were Egypt (1.35 million t from 420 000 ha), Saudi Arabia (1.08 million t; 172 000 ha), Iran (1.02 million t; 156 000 ha), United Arab Emirates (0.83 million t; 197 000 ha) and Pakistan (0.76 million t; 72,000 ha). Before the 2003–2011 conflict, Iraq produced a similar quantity of dates to each of these three leading countries. In 2010, the total planted area in the world was 1195 000 ha, producing 7.9 million t of fruit. Of this, West Asia and North Africa together produced nearly three quarters (74%) of the world total. It should be noted that many of these production and land area figures are 'estimates'.

Not only do dates provide food and nutrition for people and animals, the palms themselves are the source of materials for building and thatching roofs and for household utensils. This includes the doum palm (Figure 5.2). Dates also play an integral role in the daily cultural and religious life of people. In Iran, for example, growing dates bestows authority on farmers, whilst dates are used by almost all Muslims to break their fasting during the holy month of Ramadan. Date palm cultivation is a labour-intensive industry that makes a valuable contribution to improving and sustaining livelihoods in poor rural areas. Processing and packing facilities also create jobs, particularly for

Figure 5.1 The date palm (*Phoenix dactylifera*) is one of the oldest known fruit crops. It is subtropical in origin and cultivation – northern Nigeria (MKVC). See also colour plates section.

women. In Egypt, for example, the date industry supports the livelihoods of over one million people (FAO, 2008). When considered as a fresh fruit, the date ranks number five in the production list of tropical and subtropical crops, after citrus, mango, banana and pineapple, and, as a dried fruit, it is first (Barreveld, 1993).

In 2007, in order to find out more about what is happening to the date palm industry across the West Asia and North Africa region, FAO (2008) commissioned country studies in Algeria, Egypt, Iran, Libya, Morocco, Oman, Saudi Arabia, Tunisia, United Arab Emirates and Yemen. All these countries are largely arid (with some winter rainfall), and the date palm is therefore dependent on irrigation or a shallow water table for survival (Figure 5.3). Most dates (>90%) in the region are grown for local consumption and are extremely important as a subsistence crop. The overall trend has been a gradual move from mixed and random oasis date palm cultivation to a more intensive plantation system of production (Barreveld, 1993). In Saudi Arabia, where

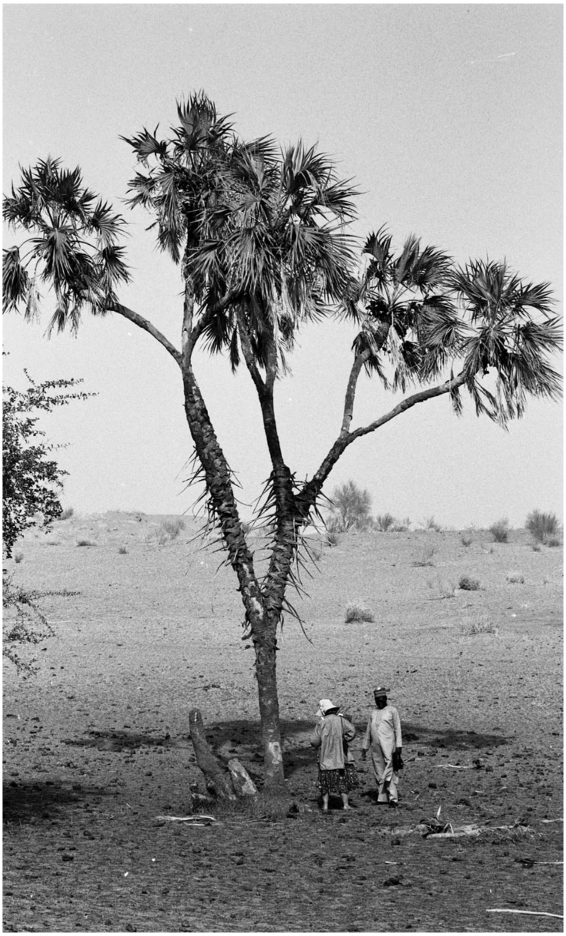

Figure 5.2 The doum palm (*Hyphaene thebaica*), the only branched palm tree, is also found along the banks of rivers and around the periphery of oases, and it too has multiple uses (see also Figure 1.16) –Nigeria (MKVC).

there is price support for low-grade varieties and subsidies for the most important production variables, such as fertilisers, farmers still find it difficult to make an investment decision on new plantings or replanting existing orchards, because of the long-term nature of the financial returns (Alshuaibi, 2011).

Countries in the West Asia and North Africa regions suffer from severe water shortages, with some 16 countries below the internationally accepted 'water poverty limit' of 500 m^3 $year^{-1}$ $person^{-1}$. This compares with a global average of 7000 m^3 $year^{-1}$ $person^{-1}$. These countries have rising populations demanding more water per capita and rely heavily on irrigated agriculture, which in many cases absorbs more than 80% of the available water resources for economic growth, employment and food security (FAO, 2008).

Despite water being a scarce resource in all the main producing countries, the water relations and irrigation requirements of such an important crop have been the focus of

Figure 5.3 An oasis in north-eastern Nigeria close to Niger border with mixed arable and palm tree crops (MKVC). See also colour plates section.

only a limited amount of research. systems. The issues identified as important in the FAO (2008) study are summarised at appropriate places in the text.

Crop development

There are thousands of named date palm cultivars, but exact numbers are not known, since we still depend mainly on tree morphology and fruit characters to distinguish between them. Using a molecular marker system, Elshibli (2010) has studied the phenotypic and genetic diversity in date palm, principally in Sudan. Although there was a significant differentiation between groups of cultivars from Sudan and Morocco, the major feature was a complete lack of clustering, and the absence of cultivars representing specific clones. Date palm populations such as these have evolved with the aid of man over the millennia. In a review of biodiversity in date palm, Jaradat (2011) highlighted the importance of conserving the genetic diversity that exists in date palm, both within and between the isolated oasis agro-ecosystems. Scientific breeding programmes, such as the one in Morocco (El Hadrami *et al.*, 2011), will hasten the process of plant improvement, whilst the role of biotechnology in the further development of date palm has been described in a recent book by Jain *et al.* (2011).

Some cultivars have become predominant in the world market. These include Deglet Noor from the Algerian Sahara; Medjool believed to be from Morocco; Barhee, from Iraq; Halawy, also from Iraq; Hayany, from Egypt; and Khadrawy and Zahidi, both from Iraq (Chao and Krueger, 2007).

Vegetative growth

As Tomlinson (2006) highlights, palms as a family are unique, possessing distinctive features of leaf development, vascular structure and anatomical properties of the stem. There is no cambium layer. The single stem develops entirely from cells derived from the apical meristem. Its structure means that it is not only a conductor of water to the leaves but also, because of its volume, acts as an important water store, or capacitor.

The date palm is propagated from seed, offshoots, the most common method, or, more recently, by tissue culture. Population densities vary from 100 palms ha^{-1} (10 × 10 m) to 400 palms ha^{-1} (5 × 5 m), whilst intercropping of date palm with fruits, vegetables and pasture is common in traditional areas of date production.

During the palm's juvenile phase, offshoots develop from axillary buds at the base of the trunk. After three to five years, the suckers grow their own roots and can then be removed and planted. The trunk, with a terminal crown of 100–120 leaves, grows up to 20–30 m in height (Figure 5.4). From 10 to 30 new leaves, each originating from the apical meristem, are produced each year. Each leaf has a variable life span of up to seven years, depending on conditions. At the base of each leaf there is an axillary bud. In mature trees, most of those just below the growing point develop during the winter as flower buds. Under cultivation, dead or old leaves are removed, leaving the leaf bases attached to the trunk. (Purseglove 1972; Barreveld, 1993; Zaid and de Wet, 2002a; Chao and Krueger, 2007).

The early work on the responses of date palm to water stress, conducted in the Coachella Valley, California, was reviewed by Hilgeman and Reuther (1967). In summary, Aldrich (1942), and Reuther and Crawford (1945) showed that, using the rate of elongation of the

Figure 5.4 The date palm has a terminal crown of 100–120 leaves. At the base of each leaf is an axillary bud, most of which develop as flower buds in the winter – California (MKVC).

central unexpanded spear leaf as an index, a shortage of soil water in the summer limited leaf extension within four weeks after an irrigation (loam soil; cv. Deglet Noor). This corresponded to about a 50% depletion of the available water in the 'major' root zone. It was also shown that reducing spear leaf extension rates by 15–20% through withholding irrigation also reduced fruit size by 10–15%, reduced the water content of the fruit and induced earlier ripening (Aldrich *et al.*, 1942; Reuther and Crawford, 1945; Furr *et al.*, 1951). Although it is not possible to specify absolute values of leaf extension, relative values were considered to be a good index of water availability.

Flowering

The date palm is dioecious, meaning that it has separate male and female trees. A much-branched inflorescence, which is a cluster of 8000–10 000 individual flowers, develops in the axil of a leaf that developed in the previous year (Figure 5.5). The inflorescence is enclosed in a deciduous hard fibrous cover (a spathe). In commerce, the palm is pollinated artificially, with pollen taken from male trees (Chao and Krueger, 2007).

Fruiting

The date fruit is a berry, with a single seed. The fruits are borne in clusters known as bunches (Figure 5.6). Female palms start to produce flowers and fruit within three to four years from planting. Natural fruit drop occurs 25–35 days after the cracking of the

Figure 5.5 The much branched date palm inflorescence is a cluster of 8000–10 000 individual flowers. This forms in the axil of a leaf that developed in the previous year. The inflorescence is enclosed in a deciduous hard fibrous cover – Nigeria (MKVC). See also colour plates section.

Figure 5.6 The date fruit is a berry, with a single seed. The fruits are borne in clusters known as bunches – California, USA (MKVC). See also colour plates section.

spathe and the emergence of the inflorescence. Fruit thinning is sometimes practised in order, for example, to decrease alternate bearing (heavy fruiting in one year followed by sparse fruiting in the next), to increase fruit size, to improve quality and to advance ripening (e.g. Al-Saikhan, 2008). The date fruit goes through four distinct ripening phases. These are known by their Arabic names: Kimri (immature green), Khalal (mature soft coloured), Rutab (soft brown) and Tamar (hard raisin-like). From pollination to maturity takes 150–200 days. In the principal producing countries, the harvest lasts from mid-August until the end of October. Fruits harvested before they are fully ripe are known as soft dates, or, if they are allowed to dry out, as hard or dry dates. Rainfall (early) during the final stages of fruit maturation can cause direct physical damage or result in secondary adverse effects, including insect and fungal infections (Figure 5.7) (Barreveld, 1993). Restricting irrigation during fruit-stalk development

Figure 5.7 Rainfall during the final stages of fruit maturation can cause direct physical damage or result in secondary adverse effects, including insect and fungal infections. Here in California, the bunches are being protected from rain with plastic cones (MKVC).

reduced the incidence of premature drying and dropping of fruit bunches (cv. Medjool) experienced in Israel (Cohen *et al.*, 2010)

The climatic requirements of date palm have been partly reviewed and summarised by Zaid and de Wet (2002b). For the production of good-quality fruit, the palm requires high temperatures (an average of 30 ºC for proper ripening (although it can survive extreme temperatures from <–6 ºC to >50 ºC)), low humidity, ample sunshine (whatever that may mean) and adequate supplies of underground water or irrigation (Purseglove, 1972). According to Pareek (1990), the ideal mean air temperature during flowering and ripening of the fruit is 25–29 ºC, depending on cultivar. For successful fruit maturation 3000 day ºC are required (in this case summed above a base temperature of 10 ºC counted from flowering). Citing other sources, Barreveld (1993) gave a figure of 1800–1900 day ºC (this time above a base temperature for the flowering process of 18 ºC, which is considered to be more realistic than 10 ºC) from pollination to harvest.

The sensitivity of date palm to the soil type was recorded by Reuther (1944) in Coachella Valley, California. Palms growing in deep sandy soils (2.7–4.8 m) responded, in terms of tree vigour, fruit yield and quality, to the application of additional frequent applications of water, compared with those growing in a soil with a deep (0.9–1.8 m) silt subsoil layer.

A fully productive tree can support at least 30 bunches. In round figures, an average yield of about 40 kg tree^{-1} is equivalent to eight bunches of 250 dates with each fruit weighing 25 g. Yields of more than 100 kg palm^{-1} are possible. Full commercial yields are reached within 10 years after planting. The average economic life of a tree is 50–60 years (Zaid and de Wet, 2002a, 2002b; Erskine *et al.*, 2005; Chao and Krueger, 2007).

Roots

Offshoots that develop at the base of the stem have a relatively high survival rate when transplanted to the field, once they have a well-developed root system. Aerial offshoots that arise higher up the main stem lack such a root system and their survival rate is lower. They are usually discarded, but can be encouraged to root by wrapping the base of the offshoot in a polyethylene bag containing wet wood shavings, whilst still attached to the tree. No periodic watering is needed. Cultivars differ in the capacity of their aerial offshoots to form roots (Al-Obeed, 2005).

In California (and Arizona), where there is a demand for date palms in the lucrative landscape market, successful establishment of (valuable) offshoots is important. In a detailed study of root development, Hodel and Pittenger (2003) found considerable variability between offshoots in establishment, which was explained by differences in root generation. Offshoots possessing more roots (>28) when removed from the mother plant had a greater capacity to regenerate a root system and to establish successfully than those with fewer roots (<24). This was in part because two-thirds of all new roots grew from existing cut roots (those damaged in the process of excision from the mother palm). Also important was the size and shape of the root initiation zone on the offshoot. Leaf extension was found to be a good indicator of root growth.

In the field, the date palm has a fibrous root system, with a mass of mainly horizontal roots in the surface 0.25 m. These roots have numerous and large air spaces, which may be why date palm tolerates flooding. Other roots extend vertically to depths of at least 2 m (Barreveld, 1993), sometimes even down to 10 m.

Root extension rates of four species of palm, but not including *Phoenix dactylifera* L., were recorded in a rhizotron in southern Florida by Broschat (1998). Roots grew continuously over the two years of observation, but less fast during the winter months. There was no evidence of alternating flushes of shoot and root growth in any of the species.

The sensitivity of the roots of the date palm to soil compaction was highlighted by Abdul-Baki and Aslan (2004). The average number of fibrous roots per mature tree was reduced from 4000 to 1100 to 520 as the degree of compaction increased. Compacted soils make date palms even more susceptible to damage by the strong winds experienced in Coachella Valley, California.

Summary: crop development

1. The single stem develops from cells derived from the apical meristem.
2. The date palm is usually propagated from offshoots that grow from axillary buds at the base of the trunk (of juvenile trees). After three to five years of attachment, these offshoots develop their own roots.
3. There is a terminal crown of 100–120 leaves; 10–30 new leaves are produced each year. Relative leaf extension is a good indicator of the degree of water stress.
4. At the base of each leaf there is an axillary bud. In the winter, in mature trees, most of those just below the growing point develop as flower buds. The date palm is dioecious.

5. Inflorescences develop on female trees in the axils of leaves that developed in the previous year. Each inflorescence can contain 8000–10 000 individual flowers. In commerce, the palm is pollinated artificially.
6. Palms start to produce fruit three to four years after planting. There are four recognised ripening phases. A productive tree can support at least 30 bunches, yielding >100 kg fresh fruit per tree. From pollination to maturity takes 150–200 days.
7. The date palm has a fibrous root system, dense in the surface 0.25 m. Roots can extend vertically to soil depths of >2 m. Root growth is sensitive to soil compaction.

Plant–water relations

Stomata occur on both leaf surfaces in approximately equal numbers, 182 mm^{-2} on the upper surface and 166 mm^{-2} on the lower surface (cv. Haiani) in parallel rows (Hussein *et al*., 2007). There are no hairs on the leaf.

Very little research on the water relations and gaseous exchange of the date palm has been reported. In Saudi Arabia, Al-Whaibi (1988) monitored diurnal changes in CO_2 assimilation and stomatal conductance of two cultivars (Sikkeri and Osaila), whilst Al-Khateeb *et al*. (2003), in a comparison of five cultivars (Kheneeizi, Khalas, Shahel, Shisho and Helali), assessed seasonal differences in photosynthesis and transpiration on leaves of different ages. In both examples there were indications of differences between cultivars in instantaneous water-use efficiencies. More recently, the effects of water stress on photosynthesis in five, one-year old, half-sibs date palm cultivars have been explored by Elshibli (2009) in Finland. Operating under conditions of controlled leaf temperature (25 ℃) and light intensity (1000 $\mu mol\ m^{-2}\ s^{-1}$), the ratio of the intercellular carbon dioxide concentration to the ambient CO_2 level was found to be higher than that expected for a C_3 plant species, being closer to that of a C_4 species. Soft and dry (hard) phenotypes (based on differences in fruit characteristics) varied in their responses to water stress. For example, soft phenotypes had higher stomatal conductances than dry phenotypes at all levels of water stress. Soft phenotypes could fix more carbon dioxide under dry conditions than dry ones. A variety of morphological responses to water stress were also observed. These included accelerated leaf senescence, fewer leaflets (pinnae) and reductions in plant height.

In Israel, Cohen *et al*. (2012) developed a methodology to estimate the water status of individual palm trees within a commercial orchard from aerial thermal images. The system was evaluated by comparing the canopy temperatures of well-irrigated palms with those of similar trees irrigated with only 20% of that amount of water (deficit irrigation) at three sites in the northern Dead Sea region during two months in the winters of 2007 and 2008. Since palm trees have large canopies with virtually no exposed soil beneath them, minimum mutual shading of leaves and no overlapping of the crowns of neighbouring trees, it was possible to monitor the relative water status of individual trees. This was achieved even though the temperature differences between the two irrigation treatments at all three sites were only 1 ℃. Differences in the elongation rate of the spear leaf (youngest, visible, still folded leaf, spiky in appearance) were not observed until about eight weeks after differential watering regimes were imposed. Since the yields from both treatments were similar, water savings in the winter months may be possible. An automated system of thermal imaging would allow blockages in a drip irrigation system to be identified, and could also be developed for irrigation scheduling.

Summary: plant–water relations

1. Only a limited amount of research has been reported on the water relations, and gas exchange processes, of date palm.
2. Stomata occur on both leaf surfaces in approximately equal numbers.
3. Interesting observations that require confirmation include:
   the photosynthetic process of date palm may be closer to a C_4 pathway than a C_3 one,
   soft and dry date palm phenotypes may differ in their responses to water stress, and
   thermal imaging could perhaps be developed to determine the relative water status of individual palm trees.

Crop water requirements

The early work in the USA on the water requirements of the date palm was reviewed by Hilgeman and Reuther (1967). Based on gravimetric soil sampling at Indio, California, Furr and Armstrong (1956) estimated the annual water use of palms (cv. Khadrawy) to be 1300–1600 mm, with monthly totals ranging from 60 mm in January (winter) to 190 mm in July (summer). Water was extracted from depths beyond 2 m. After allowing for direct evaporation from the soil surface, transpiration by weeds, irrigation inefficiencies and leaching requirements, the total annual depth of water required was estimated to be a massive 2700–3000 mm (Abdul-Baki and Aslan, 2004).

Since this early work in the USA, several attempts have been made to measure the actual water use (*ET*) of palms in West Asia and North Africa, using different techniques with mixed success. Too often the research outputs are of (limited) local value only, such as those reported by Saeed *et al*. (1986). Measuring the water use of a tree is not an easy task, but it can be done (Figure 5.8). For example, Kassem (2007) successfully monitored the water use of date palm over a season on a commercial farm in Saudi Arabia (Burida City; 26º 18′ N 43º 58′ E; alt. 720 m). Using both the Bowen ratio energy-balance method and a soil water-balance approach, he calculated the actual annual water use (*ET*) of drip-irrigated 15-year-old palms (cv. Sukariah) to be 1780 and 1640 mm, respectively. Daily *ET* rates (averaged over a minimum of 20 d) varied between about 2.4 mm d^{-1} in February (at pollination) and about 7.6 mm d^{-1} in July (at the Khalal – mature soft fruit – stage). The corresponding crop coefficients ($K_c = ET_c/ET_o$) were 0.63 (February) and 0.70 (Khalal). USWB Class A evaporation rates peaked at 14.1 mm d^{-1} in July.

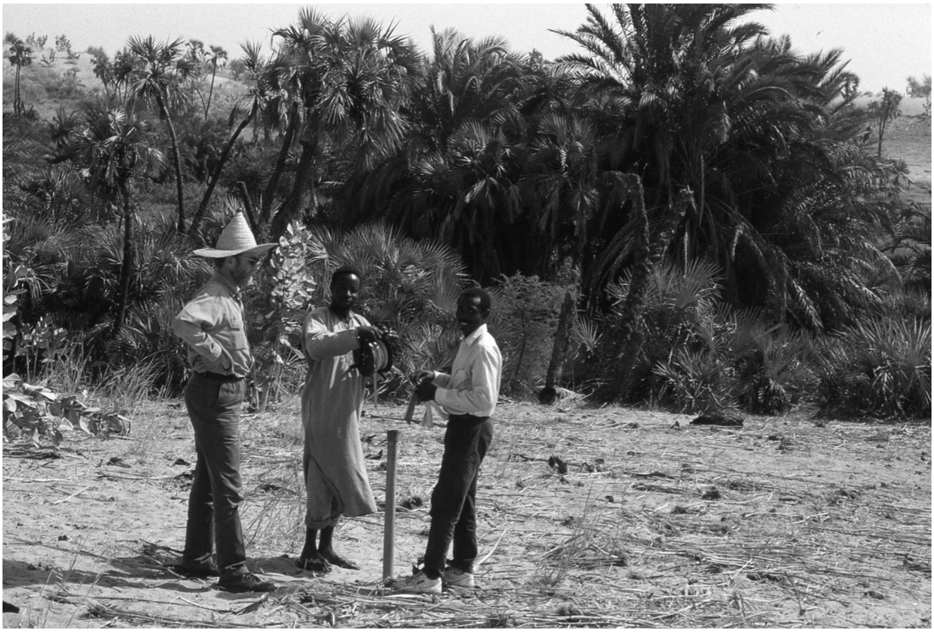

Figure 5.8 Monitoring the depth to the water table with a piezometer to assess rates of recharge and sustainable abstraction at an oasis in the Manga Grasslands in north-east Nigeria (MKVC).

This research was followed up by a comprehensive analysis of the water use of date palm at seven representative sites in Saudi Arabia (Al-Amoud *et al.*, 2012). At each site, which extended from Najran in the south (17º 28′ N 44º 06′ E; alt. 1264 m) to Qseem in the north (26º 20′ N 43º 59′ E; alt. 179 m) the actual water use by a reference crop (alfalfa), ET_r, was measured over a three-year period (2005–2007) with drainage lysimeters (measuring 2 × 2 × 1.5 m deep). These data were compared with estimates of reference crop evapotranspiration (ET_o) calculated with the FAO version of the Penman–Monteith equation (Allen *et al.*, 1998), using data collected by automatic weather stations at each site. At the same time, the actual water use of (drip) irrigated palms (ET_c) was measured using the water-balance method. The results were averaged over the three years. The measured (ET_r) and calculated (ET_o) reference crop evapotranspiration followed the same monthly trend during the year, but ET_o estimates were consistently less than ET_r (by about 20%). Daily ET_r values across the seven sites ranged from 1.7 mm d^{-1} (in January) to 11.7 mm d^{-1} (in mid-summer), whilst the annual totals fell within the range 2254 mm (at Makkah) and 3024 mm (at Wadi Addwaser). By comparison, the corresponding totals for the actual water use of date palm (ET_c) were 2136 mm and 2829 mm. After allowing for the partial wetting of the root zone using drip irrigation (*c.* 30%), these numbers equate to 600 and 800 mm, respectively or, for a density of 100 plants ha^{-1}, 60 and 80 m^3 $tree^{-1}$ (Ahmed Al-Amoud, personal communication). These values are low compared with flood irrigation and assume that drip-irrigated palms use less water than flood-irrigated plants (see below). Across the seven sites, K_c, when based on ET_r, averaged over the year between 0.89 and 0.93. Within a year, the monthly range of values was from 0.81 to 0.99, with a grand mean of 0.91. However, if K_c is based on the Penman–Monteith estimate of ET_o, rather than ET_r, it has a grand mean value of 1.18. This is very different from the corresponding K_c values reported by Kassem (2007), and described above, of 0.63 and 0.70, and also exceeds the value suggested by Allen *et al.* (1998) of 0.90–0.95.

Al-Amoud *et al.* (2012) also illustrated, with examples, the impact of two (assumed) irrigation application efficiency values (70% for basins, 90% for drip) and leaching requirements for four different salt contents of the irrigation water, based on electrical conductivity measurements (0.5, 1.0, 2.0 and 3.0 dS m^{-1}), on the gross irrigation water requirements at each of the seven sites in Saudi Arabia.

Using a simple water-balance approach, actual evapotranspiration (ET) rates by 11-year-old palms (cv. Medjool) were monitored by Mazahrih *et al.* (2012) in Jordan (32° 00′ N 35° 18′ E; alt. −224 m) over twelve months (2011). A neutron probe was used to monitor changes in soil (clay) water content to depths of 2.5 m. Rainfall over the year totalled 245 mm. Estimates of reference crop evapotranspiration (ET_o) were obtained from the Penman–Monteith equation. ET_o peaked at about 8.8 mm d^{-1} in July (January = 2.7 mm d^{-1}), with an annual ET_o total of 1900 mm. By comparison, the measured annual ET totals by palms subjected to four drip-irrigated water regimes (50, 75, 100 and 125% × ET_c replacement) were 1300, 1600, 1800 and 2000 mm, respectively. Seasonal totals of water applied were 27, 40, 53 and 67 m^3 $tree^{-1}$ (156 trees ha^{-1}). Monthly values for the crop coefficient ($K_c = ET_c/ET_o$) for the 100% ET_c replacement treatment ranged from about 0.75 in the winter, to 1.0 in the spring and 1.10 in the summer. Average annual K_c values for each treatment were 0.68, 0.84, 0.95 and 1.05, respectively. Soil salinity levels increased in the two deficit irrigation treatments.

Oases

In southern Tunisia, many traditional date palm plantations surround oases. At one of these (Tozeur; 33° 55′ N 8° 6′ E; alt. 87 m), Sellami and Sifaoui (2003) successfully used the sap-flow method to monitor transpiration (T), on a diurnal basis, of two date palms and two intercropped, understorey apricot trees. In October, the daily transpiration totals averaged 1.91mm d^{-1} for date palm (≡ 240 L d^{-1} $tree^{-1}$, at a density of 80 trees ha^{-1}) and 1.20 mm d^{-1} for apricot (≡ 75 L d^{-1} tree $^{-1}$, at 160 trees ha^{-1}), with a combined total of 3.11 mm d^{-1}. These values represented 32%, 21% and 53% of the incoming solar radiation being used for transpiration, and 53%, 33% and 88% of the net radiation, respectively. Prior to this research, Ringersama *et al.* (1996) had shown that measuring sap flow (using the Granier method) successfully demonstrated the diurnal sap flow pattern of date palms in southern Tunisia, and gave a reasonable indication of absolute transpiration rates.

The Granier method was subsequently used by Ben Aïssa *et al.* (2009) to measure sap flow in four individual date palms at Fatnassa oasis in Tunisia (33° 8′ N 8° 7′ E). Transpiration rates (T) averaged about 0.5 mm d^{-1} in the winter (daytime temperature range 9–19 °C) and 3.5 mm d^{-1} in the summer (24–42 °C), with an annual average of about 2 mm d^{-1}. In the winter, the diurnal variation in T matched the changes in ambient temperature, but in the summer T began to decline when temperatures exceeded about 32 ºC, suggesting some form of stomatal control of transpiration rates. The annual transpiration total of about 730 mm was only 40% of the potential ET_c total of 1800 mm for the location. These relatively low rates of water use were supported by measurements made in piezometer tubes of changes in the depth of the water table over periods of a month between irrigations.

The eddy-correlation and energy-budget methods were used to make continuous measurements for over a year of actual evapotranspiration from a heterogeneous canopy of an oasis ecosystem in the central Syrian desert (Palmyra; 34º 32′ N 38º 16′ E; alt. 375 m). The whole oasis covered an area of about 1000 ha and the main cultivated crops were olive trees (250 000), date palms (70 000), pomegranate trees (80 000) and other fruit trees (25 000). The tree density was 170 ha^{-1}, and bare soil, which was always unshaded, covered 60% of the land area. Measurements were made in an area with a fetch of about 1 km in all directions. On a monthly basis, actual ET ranged between 0.5 mm d^{-1} in the winter and 3.5 mm d^{-1} in mid-summer (annual $ET_o = 1700$ mm). On a daily basis, actual ET never exceeded 5 mm d^{-1}. There was a time lag of three days between an irrigation event (flood, applied at intervals of 28 days) and an increase in transpiration by the vegetation (due possibly to a delay in full stomatal opening). By contrast, winter rainfall (average 120 mm y^{-1}) had an immediate effect on evapotranspiration. Interestingly, ET (hourly averages) increased with increases in wind speed up to 3 m s^{-1} and then decreased as wind speed increased to 6.5 m s^{-1}, due, it was claimed, to wind-induced stomatal closure (Brunel *et al.*, 2006).

Regional estimates

According to the FAO (2008) report, most countries assess date palm water requirements using some form of theoretical calculation, such as the Penman–Monteith equation, or USWB Class A evaporation pan data. Some make assumptions about the efficiency of the irrigation method to arrive at gross water requirements. This is because very few actual data are available from field or lysimeter measurements. The data available on irrigation water requirements vary considerably from one country to another and even within a country, principally as a result of the differences in climate. There is also the risk that the figures being compared are not in fact directly comparable. Algeria, for example, reports that the annual water demand for mature trees varies from 1300 mm in Batna, an important date-growing area in the north of the Sahara, to 3100 mm in Adrar in the arid south. The corresponding average water requirements are 300 L d^{-1} $palm^{-1}$ in Batna and 700 L d^{-1} $palm^{-1}$ in Adrar, assuming a typical planting density of 120 palms ha^{-1}, with peak values in July 50% greater than these. For comparison, in the same FAO (2008) report, it is estimated that, within the region represented in the survey, there are in excess of 120 million date palms using 19 500 million m^3 of water annually (equivalent to one third of Egypt’s annual share of the Nile water). This equates to 445 L $tree^{-1}$ day^{-1}.

Egypt also reports considerable variation in water demand across the country. Dates grown in Lower Egypt use an average of about 1000 mm a year, whereas in Upper

Egypt average consumption rises to 1500 mm a year. Current estimates of water use of palms in Morocco (planted at 100 palms ha^{-1}) are 1300–1400 mm a year. In Saudi Arabia, estimates of irrigation water requirements (gross) range from 1800 mm a year for drip-irrigated palms, to 4300 mm a year for surface irrigation. This difference is based in part on the (sometimes false) assumption that palms irrigated by drip systems *use* less water than those irrigated by surface methods.

In Saudi Arabia, Alazba (2004) used the Penman–Monteith model to estimate the water use (ET_c) of date palm at seven sites. Using a fixed K_c value of 0.85 he found that the annual ET_c totals varied between sites from 1500 to 2000 mm. If the irrigation efficiency is assumed to be 40% and an additional 10% is allowed for leaching, the maximum irrigation water requirement is 5500 mm. If, instead, the efficiency is 90% and no allowance is made for leaching, the corresponding irrigation water requirement is 2200 mm.

Liebenberg and Zaid (2002) provide worked examples of how to estimate the irrigation water requirements of date palm. The annual ET_c totals listed include 2400 mm for Tozeur, Tunisia, and 2200–2400 mm for Naute, Namibia, with peak daily rates of about 10 mm d^{-1}.

Intercrops

Intercropping date palm in either a two-tier system (with a fruit tree crop) or a three-tier system (with fruit trees and an annual crop) is a common, traditional agricultural practice (Figure 5.9). It adds a complication to assessing crop water requirements. Indigenous knowledge associated with this diversity and its management is critical in sustaining the viability of the oasis (Jaradat, 2011). This includes managing water in a sustainable way.

In the FAO manual on crop evapotranspiration, Allen *et al.* (1998) provide examples of specific situations that are particularly relevant to date palms. For example, they show how to compute the water requirements of a date palm/citrus tree intercrop, where the canopy of one crop (palm) is well above the other (citrus) so that the canopies cannot be seen as contiguous. They also consider the case of the so-called ‘clothes-line’ effect (where small areas of vegetation, e.g. palms, are substantially taller than the surroundings), and the ‘oasis’ effect (where vegetation has access to more water than the surroundings). In both cases, ET_c can be substantially greater (100% or more) than that for a reference (grass) crop, as a result of advection (the lateral transfer of sensible heat from the surroundings). The magnitude of this effect depends in part on the width of the vegetation in relation to the wind direction, with K_c values of up to 2.5 close to the leading edge.

Summary: crop water requirements

1. Several attempts to determine the water requirements of date palm have been reported, both for conventional irrigated conditions and for situations where there is a high water table, as found close to oases. In addition, regional estimates have been calculated.

Figure 5.9 Intercropping date palm in either a two-tier system (with a fruit tree crop, as in this example) or a three-tier system (with fruit trees and an annual crop) is a common, traditional agricultural practice –northern Nigeria (MKVC).

2. A range of techniques (each with different assumptions) has been used, making direct comparisons difficult (Table 5.1).
3. Water can be extracted from soil depths >2 m.
4. Across West Asia and North Africa calculated/estimated annual ET_c totals are (mainly) in the range 1000–2000 mm.
5. In southern Tunisia, transpiration (T) rates varied from 0.5 (winter) to 3.5 (summer) mm d^{-1}. In winter, the diurnal variation in T matched the changes in ambient temperature, but in summer T declined when temperatures exceeded about 32 ℃, suggesting some form of stomatal control of transpiration rates.
6. In Syria, ET on a monthly basis ranged from 0.5 (winter) to 3.5 (summer) mm d^{-1}; on a daily basis ET did not exceed 5 mm d^{-1}. In Saudi Arabia, the corresponding

Table 5.1 Comparisons of crop water use estimates for date palm – see text for details

Site		ET_o (mm)	ET_c (mm)	ET (mm d^{-1})	T (mm d^{-1})	K_c	Method		Ref.
Southern Tunisia	Oasis				1.9/3.1 (Oct)		Sap flow	Intercrop apricot	1
Southern Tunisia	Oasis		1800		0.5–3.5 Σ730 (mm)		Sap flow	Monocrop	2
Syria	Oasis	1700		0.5–3.5			Micromet.	Intercrop fruits	3
Saudi Arabia	Farm	14.1(mm d^{-1}, peak)		2.4–7.6 1700 (mm)		0.63–0.7	Micromet. & water balance	Monocrop	4
Algeria	Regions		1300–3100				Estimate		5
Egypt	Regions		1000–1500				Estimate		5
Morocco	Regions		1300–1400				Estimate		5
Saudi Arabia	Seven sites		1500–2000			0.85	Penman–Monteith	Monocrop	6
California	Farm			1300–1600			Soil water balance	Monocrop	7

References: 1.Sellami and Sifaoui (2003) 2. Ben Aissa *et al*. (2009) 3. Brunel *et al*. (2006) 4. Kassem (2007) 5. FAO (2008) 6. Alazba (2004) 7. Furr and Armstrong (1956).

values were about 2–3 and 8–11 mm d^{-1}, depending on location. In Jordan, ET rates were 1.9–2.3 mm d^{-1} in the winter and 7.6–9.9 mm d^{-1} in the summer.

7. Experimentally determined values of the crop coefficient ($K_c = ET_c / ET_o$) in Saudi Arabia were inconsistent. In one experiment, K_c = 0.6–0.7, but in a series of experiments K_c averaged 1.18. But, when K_c was based on a measured reference crop value for ET_o, as opposed to a calculated value, $K_c = 0.9$. In Jordan, K_c varied with the season: 0.75 in the winter, 1.0 in the spring and 1.10 in the summer.
8. The so-called ‘clothes-line’ effect and the ‘oasis’ effect mean that in some situations K_c can be substantially greater than 1.0 as a result of advection.
9. Interesting observations that require confirmation include:
   (a) there is a time lag of three days between an irrigation event and an increase in transpiration, but winter rainfall has an immediate effect;
   (b) at wind speeds >3 m s^{-1}, there is an indication that wind-induced stomatal closure restricts transpiration.

Water productivity

In order to evaluate the benefits to be derived from irrigation some measure of the water productivity is needed. Only two experiments have been reported where an attempt has been made to quantify the benefits in this way. In Aswan, Egypt, the responses of 24-year-old Sakotti palms to four irrigation regimes were compared over two years (1968 and 1969) by Hussein and Hussein (1982). The watering treatments were described as six applications of 180 mm every eight weeks (annual total = 1100 mm); 12 applications of 180 mm at monthly intervals (total 2200 mm); 24 applications of 180 mm at two-week intervals (total 4400 mm) plus a no-irrigation control treatment (no mention is made of any water inputs from flood water or a water table or of the evapotranspiration rates). Averaged over both years, yields of fresh fruit increased from 55 kg $tree^{-1}$ (control), through 71, 83 and 90 kg $tree^{-1}$ as the quantity of water applied increased. The total soluble solids and moisture contents of the fruit were also increased with irrigation, but fruit maturity was delayed by up to 15 days. The advice was to apply 12 × 70 mm irrigations a year at four-week intervals. It is not clear on what basis this conclusion was reached. This experiment has limited generic value.

In central Saudi Arabia, Al-Amoud *et al.* (2000) compared three levels of water application (50, 100 and 150% times evaporation from a USWB Class A pan) applied at two-week or, in the spring and summer months, one-week intervals. Three irrigation methods (trickle, bubbler and basin) were also compared within the same experiment (see below), which continued for four years (1991–1994). The soil was a sandy loam. In round figures, the total annual average depths of water applied were 1000, 2000 and 3000 mm to each of the three watering treatments. The average yield across all nine treatment combinations over the four years was 173 kg $tree^{-1}$. Trees irrigated with trickle out-yielded those irrigated by the other two methods in some years, but not all (overall by about 20%). Yield responses to the three water treatments were inconsistent.

The resultant irrigation water productivity values varied between 0.55 (at 150% E_{pan}) and 1.40 kg m^{-3} (at 50% E_{pan}) (FAO, 2008).

According to the same FAO (2008) report, the highest date palm water productivity is in Egypt, with values from 1.3 to 3.3 kg m^{-3} of water applied. This is significantly greater than all the other countries for reasons, in part, given earlier (soft dates with a water content of 40–50%). By contrast, the range of values for hard-date-producing countries in the region is only 0.18–0.37 kg m^{-3}. Expressed in another way, this means between 3 and 5 m^3 (or 3 to 5 tonnes) of water are needed to produce 1 kg of fresh fruit!

In Jordan, water productivities over one year declined from 1.25 to 0.64 kg m^{-3} as the amount of irrigation water applied increased (50, 75, 100 and 125% ET_c). The corresponding yields of fresh fruit were 34, 36, 38 and 43 kg $tree^{-1}$ (Mazahrih *et al.*, 2012).

In Saudi Arabia, a typical yield from a commercial farm is 90 kg fresh fruit $tree^{-1}$ whilst the annual gross amount of water applied (drip irrigation) rarely exceeds 120 m^3 $tree^{-1}$, and can be as little as 70 m^3 $tree^{-1}$. These represent water productivities of 0.75 and 1.3 kg m^{-3} (Ahmed Al-Amoud, personal communication). These are similar to the values obtained in Jordan.

Citing others, Barreveld (1993) presented indicative figures for the irrigation requirements and water productivity of date palm in the following practical and instructive way. For example, when water is applied continuously over a year at a rate of 0.5 L $palm^{-1}$ $minute^{-1}$, this equates to 250 m^3 $palm^{-1}$ $year^{-1}$. If one ox (or a man) can lift water from 20 m depth at a rate of 2 m^3 h^{-1}, this represents 125 h work per year per tree. For a crop yielding 100 kg tree $^{-1}$, this equates to about one and a quarter hours of human effort lifting water to produce 1 kg of fruit (or 2.5 t of water to produce 1 kg of fruit).

Summary: water productivity

1. There is very little published experimental evidence on the water productivity of date palm.
2. A target benchmark figure for hard dates is probably of the order 1.3 kg fresh fruit m^{-3} irrigation water applied.

Salinity

Following a review of the literature, Maas and Hoffman (1977) classified the date palm as being ‘salt tolerant’. They specified the threshold electrical conductivity of the saturated soil extract (EC_e), above which fruit yield was reduced, as 4.0 dS m^{-1}. The rate of fruit yield decline if this value was exceeded was estimated to be 3.6% (dS $m^{-1})^{-1}$. These two values were based on the results of experiments conducted in California and reported in the 1960s by Furr and Armstrong (1962), Furr and Ream (1968) and Furr *et al.* (1966). They are both relative values, dependent on the cultural conditions under which the crop is grown. Despite the limited information base, the same values were later repeated by Maas (1993) in an updated list, and are the ones always cited in papers on salinity (e.g. Ayers and Westcot, 1985; Rhoades and Loveday, 1990). Based on these two criteria, date palm is classified as the most salt-tolerant fruit crop, and possibly the second most salt tolerant of all the major crop plants (after barley).

This view has, however, recently been challenged by the results of a detailed, long-term, lysimeter-based research programme in the Southern Arava region of Israel (29º 53′ N 53º 03′ E) reported by Tripler *et al.* (2007; 2011; 2012).This is an arid area (mean annual rainfall only 25 mm), with summer temperatures reaching 40 ºC and relative humidity as low as 15%. Over a period of seven years from 1999, the effects of elevated salinity levels in the soil solution on water use, growth and fruit yield of date palms (cv. Medjool), growing in 20 large (initially 1 m^3, later increased to 2.5 m^3 and then to 10 m^3) high-resolution weighing, drainage lysimeters, were monitored. Irrigation water with electrical conductivities (EC_i) of 1.8, 4.0, 8.0 and 12 dS m^{-1} was applied daily. Salinity reduced evapotranspiration (ET_c) at all levels, as represented by a series of sigmoid curves. The extent of this reduction increased over time such that, in the final three years of the experiment, ET at the highest salinity level (12 dS m^{-1}) was only about 10% of the maximum for non-stressed trees ($EC_i = 1.8$ dS m^{-1}). Water uptake by the roots was restricted by the reduction in osmotic potential due to the presence of salts in the soil water, not to ion toxicity. All aspects of vegetative growth were reduced by salinity, including the rate of production of new leaves, which, in the final years of the experiment, declined from 40 $year^{-1}$ to 20 $year^{-1}$, and the extension rate of the newest leaves (from 40 mm d^{-1} to 12 mm d^{-1}). Together these responses to salinity resulted in a reduction in the size of the leaf canopy (Tripler *et al.*, 2007; 2011).

Fruit production was also affected. Trees in the low-salinity treatments began to produce fruit in 2005, whereas those exposed to high salinity levels did not bear fruit until 2007. Fruit maturity was also delayed by about two weeks. Plotting fruit yield over the final two years against the electrical conductivity of the irrigation water, when responses had stabilised, showed the soil salinity level that reduced yields by 50% to be about 4.7 dS m^{-1}. By comparison, the corresponding value for the data presented by Maas (1993) was 18 dS m^{-1}. The date palm, on the basis of this information, is more sensitive to salinity than previously thought (Tripler *et al.*, 2011). An annual crop yield model to predict drainage-water salinity levels and leaching fractions has been successfully calibrated and validated (Tripler *et al.*, 2012).

In some areas of Saudi Arabia date palms are grown in soils where the EC_e reaches 20 dS m^{-1}. The electrical conductivity of the irrigation water in the main aquifers in Saudi Arabia is 2–5 dS m^{-1} (FAO, 2008). Similarly, salinity is an issue in the irrigated cropped areas surrounding oases in Tunisia (Ben Aïssa *et al.*, 2004). The application of 900 mm of water over a season (April to October) contained, for example, the equivalent of 28 t ha^{-1} of salt. The salinity of the irrigation water varied with the depth from which the water was abstracted. The results of the study emphasised the need to improve water management by modernising the irrigation methods and by introducing effective drainage.

In the Wargla river basin in Algeria, Bouhoun *et al.* (2011) attempted to distinguish the separate and combined effects of waterlogging and salinity on date palm yields (cv. Deglet Noor), as recorded in 167 field plots located in five irrigation sectors. Saline irrigation water and shallow water tables both increased soil salinity. Actual yields decreased with increases in soil salinity, shallow water tables, and the presence or otherwise of a gypsum-cemented horizon within the soil profile. A significant interaction between water table depth and soil salinity suggested that the crop responded to whichever stress factor was the most severe rather than to a combination of the individual factors. The limiting factors in order of decreasing importance were shallow water table (38% of the field plots), high soil salinity (17%) and the occurrence of a gypsum-cemented horizon (2%). No limiting factors to yield were identified in the remaining field plots (43%). In some sectors, actual yields were far below potential yields, which may have been due to the adverse effects of irrigation water salinity.

In Iran, Tishehzan *et al.* (2011) used 36 drainage lysimeters to study the effects of water table depth (0.60 m and 0.90 m), groundwater salinity (4, 8 and 12 dS m^{-1}) and mulching (with and without date palm leaves) on the growth of young date palms (cv. Berhii). By restricting evaporation from the soil surface, mulching limited the accumulation of salts in the root zone, and reduced the harmful effects of a shallow, saline water table on leaf growth.

In a superficial review of the impact of salinity on date palm, Alhammadi and Kurup (2012) highlighted the need to find ways of screening the many cultivars of date palm (over 1500) for salinity tolerance at different stages of growth. Cultivars do differ in their responses to salt, particularly at the seedling stage. They advocated the use of remote sensing for detecting salinity stress in date palm orchards.

Summary: salinity

1. The date palm is considered to be relatively salt tolerant with a threshold EC_e value of 4.0 dS m^{-1}, but recent evidence from Israel suggests that it is more sensitive than originally thought.
2. Saline irrigation water and shallow water tables both increase soil salinity.
3. The date palm responds to the most severe stress (e.g. a shallow water table) rather than to the influence of a combination of waterlogging and high soil salinity.
4. Mulching limits the accumulation of salts in the root zone, and reduces the harmful effects of a shallow, saline water table on leaf growth.

Irrigation systems

Originally, the majority of the old date palm orchards (in Saudi Arabia) were irrigated from wells using surface irrigation methods, especially basins. Water was lifted from hand-dug wells, 5–15 m deep, using the *swani* method, in which 1–4 camels or cows

Figure 5.10 A traditional system of lifting water for irrigating date palms in Egypt (HDT).

provided the power, via a circular wheel, to lift the water in buckets made from animal skin connected by ropes made from date palms (Figure 5.10). The water was delivered to the palms in ditches. A farm was usually irrigated once a week in the summer and every three weeks in the winter. This is one example of the various irrigation methods used throughout the West Asia and North Africa regions and described in some detail in FAO's country studies (FAO, 2008).

Flood or surface irrigation is cited as still the most commonly method used, continuing a long tradition. Egypt, for example, still irrigates about 90% of its date palms with surface methods, particularly on the so-called 'old lands'. Many palms are grown along the borders of farms in Egypt, where they are managed as part of the farm cropping system. This may be true in many other countries, particularly where palms are grown in areas with shallow groundwater, such as oases. Sprinkler irrigation is not widely used, although micro-sprinklers play a growing role in some countries, particularly on sandy soils (Figure 5.11). Drip irrigation is the method that is of most interest to governments because of its reputation for reducing the irrigation water requirement. The productivity of drip irrigation is, however, as much a function of how well it is managed as it is of the system itself. Most countries in the West Asia and North Africa region are now experimenting with drip irrigation, which is being supported through government subsidies (FAO, 2008).

In the Coachella Valley, California (2800 ha of palm; 123 palms ha^{-1}) the standard method of irrigation for mature palms is basin with 120–150 mm water applied every 12–14 days during the growing season. Irrigation is reduced about two weeks before

Figure 5.11 Sprinkler irrigation is not widely used with date palm, although micro-sprinklers play a growing role in some countries, particularly on sandy soils – Israel (MKVC).

harvest. With newly planted orchards, drip irrigation is used for the first five years (Abdul-Baki and Aslan, 2004).

In Saudi Arabia, Al-Amoud (2008) compared the performance of bubbler irrigation[1] with trickle in a large-scale farm trial (6000 trees on a farm with >200 000 trees). The bubbler system was designed to deliver water to each tree at 12 L min^{-1}, but the uniformity of distribution of water was only 62%. By comparison, the trickle system, with a design application rate from four drippers of 0.4 L min^{-1}, had a 97% uniformity of distribution. Improvements in the design of the bubbler system were considered possible, but, on the basis of the evidence obtained, it was concluded that a well-designed and managed drip-irrigation system was suitable for irrigating large date palms in Saudi Arabia.

In Saudi Arabia, Ahmed *et al.* (2011) compared the performance of subsurface trickle-irrigation systems with pipes of varying wall thickness/flexibility buried at a depth of 0.4 m. With flexible pipes (thin walls, 0.41 mm thickness) leakage occurred and water was wasted. Date palms irrigated through these pipes yielded substantially less, and the water applied was less productive than when water was applied through rigid pipes (thick walls, 1.14 mm thickness) (Ahmed *et al.*, 2012). The considerable water saving (i.e. water not used for the purpose intended, Perry, 2011) from subsurface drip irrigation, compared with a conventional system, as well as a yield advantage, were confirmed by Al-Amoud (2010) in a long-term laboratory and field study (2001–2008), again in Saudi Arabia.

In Algeria, localised irrigation (e.g. drip, micro-sprinklers and bubbler systems) was first introduced in the 1980s, and between 2000 and 2005 the area of date palms irrigated with these methods increased from 320 ha (0.3%) to 56 000 ha (38%), encouraged by government subsidies. There is a common belief amongst farmers that drip irrigation does not deliver enough water to the crop. Bubbler irrigation appears to be more acceptable, as farmers can see the water being applied.

In oases, most of the water for crops comes from natural groundwater and in some coastal areas rising tides push water into date palm plantations. In other places, such as Yemen, various systems of harvesting rainwater either from surface runoff or from underground sources are used. These traditional water resources have been developed over many years into highly sustainable 'irrigation systems' (FAO, 2008).

In southern Tunisia, a participatory approach was adopted by Ghazouani *et al*. (2009) to identify the causes of low date palm productivity on a community-managed oasis. Farmers' perceptions, and the views of the engineers who had been involved in the implementation of an irrigation-system modernisation programme, were solicited on why the project had failed to achieve the expected benefits. Farmers were aware of the constraints to production due to waterlogging, and also to the adverse effects of hot irrigation water (60–70 °C; extracted from geothermal wells). Extended intervals between irrigations were cited as the main constraint, but this could be resolved by the community agreeing to restrict expansion of the date palm area. Farmers failed to mention salinity and soil degradation as causal factors. It was recommended that, in order to improve the process of modernisation, farmers' knowledge of the issues should be combined with the expertise of engineers.

This study was followed by a fascinating and detailed evaluation of irrigation performance on the same oasis (Fatnassa) by the same team (Ghazouani *et al*., 2012). The date and duration of an amazing 2836 irrigation events over a period of one year were recorded at the farm level on 419 plots. In addition, 163 observation wells were used to characterise the depth and salinity of the shallow groundwater over a two-month period. At the project level, irrigation intervals were twice (36–52 days) those that were expected (19–21 days). This was because farmers took twice as long (17–20 h ha^{-1}) to irrigate a field as planned (10 h ha^{-1}). At the field level, this was due to several factors, including small fields, poor maintenance, night irrigation and lack of farmer commitment to collective rules. The study highlighted issues such as inequity among farmers and the risk to the sustainability of irrigation as the groundwater is depleted.

Summary: irrigation systems

1. Since early times, flood irrigation has been used to irrigate date palm and, in many countries, it is still the most commonly used method.
2. In oases, most of the water for crops comes from natural groundwater, and in some coastal areas rising tides push water into date palm plantations.
3. Since the 1980s, localised irrigation (e.g. drip, micro-sprinklers and bubbler systems) has been promoted by governments to date palm farmers as a means (in theory) of saving water.

4. Considerable water savings, as well as yield advantages, have been recorded from subsurface drip irrigation, compared with a conventional system.
5. In order to improve the process of irrigation modernisation, farmers' knowledge of the issues needs to be combined with the expertise of engineers.
6. A participatory study of irrigation on a community-managed date palm project highlighted as significant issues the inequity among farmers and the risk to the sustainability of irrigation, as the groundwater is depleted.

Conclusions

In desert oases, the sustainability of date palm and the associated crops can only be ensured if the available water resources are managed well. As a result of the FAO (2008) review, a number of recommendations were made. Many of them are endorsed by this review. Because of the regional and international importance of date palm, the following issues need to continue to be addressed:

- Determination of factors influencing the water requirements of date palm
- Requirement for fundamental studies on plant–water relations to enable valid comparisons to be made between sites and cultivars
- Quantification of the yield response to deficit irrigation (and to low-quality water)
- Realistic in-depth assessments of the current levels of irrigation water use, the performance of irrigation systems and the way farmers and system managers manage irrigation

Figure 5.12 A high-value date crop on sale in California, USA (MKVC).

- Promotion of new technologies designed to improve water productivity, but which are largely unknown among date palm growers
- Collation of existing knowledge, good practices and research results from the different countries in the form of a practical manual on the irrigation of date palm.

Water scarcity in the West Asia and North Africa regions is extreme. With rainwater being limited and groundwater being depleted, most of the date-producing countries are increasingly dependent on desalinisation of seawater, which is expensive. Only high-value crops suited to the harsh environment, and with high water productivities, can be justified as sustainable (Figure 5.12). The date palm, being indigenous to this region meets these criteria, but local irrigation practices are often inefficient. Adaptive research at the local level is needed to develop options to improve water productivity (after Oweis, 2004).

Summary

Date palm is a crop suited to hot, arid regions. It originated in Mesopotamia and the centres of production are in West Asia and North Africa. Despite its regional and international importance, and its dependence on irrigation or a shallow water table for survival, relatively little research has been published on the water relations and irrigation needs of date palm. Following early work in California, the majority of the recent research reported in the literature has been conducted in Saudi Arabia and Tunisia.

The date palm has a terminal crown of 100–120 leaves. At the base of each leaf is an axillary bud, most of which develop in the winter as flower buds. It takes 150–200 days from pollination to fruit maturity. Stomata occur on both leaf surfaces. Different techniques have been used to measure the water use of date palm, including micrometeorological and sap-flow methods. In Syria, mean actual evapotranspiration (ET) rates varied between 0.5 (winter) and 3.5 mm d^{-1} (summer), in Saudi Arabia from 2–3 to 8–11 mm d^{-1}, depending on location, and in Jordan from 2 to 8–10 mm d^{-1}, respectively. In Tunisia, there was some (limited) evidence of stomatal control of transpiration (T) rates (seasonal range 0.5 to 3.5 mm d^{-1}) when temperatures exceeded 32 °C. Experimentally determined values of the crop coefficient (K_c) were inconsistent, varying from 0.6–0.7 to 1.18. In the vicinity of an oasis, advection may increase potential water use (ET_c) substantially above that of a reference crop (ET_o). In the absence of a shallow water table, roots can extract water from soil depths greater than 2 m. There is little published information on the water productivity of date palm. A target benchmark figure is probably about 1.3 kg fresh fruit m^{-3} of irrigation water applied. Under controlled conditions, phenotypes differed in their responses to water stress. The date palm is traditionally considered to be relatively salt tolerant, with a threshold electrical conductivity value for the saturated soil extract of 4.0 dS m^{-1}, but recent evidence from Israel suggest this view may be mistaken. Since early times, flood irrigation has been used to irrigate date palm and it is still probably the most common method in many countries. Since the 1980s, farmers have been encouraged by governments to use localised irrigation methods (e.g. micro-sprinklers, drip and bubbler) as a means of saving water. Since water is a scarce resource in the West Asia and North Africa regions, research should focus on developing ways to improve the water productivity of this high value crop.

Endnote

1 A system of micro-irrigation developed for orchard crops, and first described by Rawlins (1977).

6 Lychee[1]

Introduction

The cultivated lychee (litchi) is a rainforest species that is believed to have originated in the region between southern China, northern Vietnam and Malaysia, between latitudes 23° N and 27° N (Mitra and Pathak, 2010). It has been cultivated for at least 4000 years in southern China and South-east Asia, but it is relatively new elsewhere, having only been introduced into Africa and the Americas during the nineteenth century. The tree is grown for its clusters of small red fruit (Figure 6.1). Fruit production is greatest in warm subtropical areas, with cool, dry winters. In hot, moist tropical locations, the trees grow, but do not flower. It is now grown commercially between latitudes 17–32° N and S, at low altitude in the subtropics and (normally) at altitudes from 300–600 m in the tropics (Menzel and Simpson, 1994a). Wild trees can still be found in the rainforests on Hainan Island (17° N), mainly at elevations of 600–800 m, in the west of Guangdong and the east of Guangxi provinces in southern China, and in the forests of northern Vietnam (*c*. 21° N). Some of these trees are 30 m tall, with a girth of 2 m, and with well-developed buttress roots (Hieke *et al*., 2002a). In these areas, winters are short, dry and relatively cold, but free of severe frosts, whilst summers are long and hot, with high rainfall and humidity above 80% (Hai and Dung, 2002).

The proceedings of a report of a meeting organised by the Food and Agricultural Organisation of the United Nations to review lychee production in the Asia-Pacific region included summaries of the state of the industry in nine countries (Papademetriou and Dent, 2002). Since then, Mitra and Pathak (2010) have published similar figures for this region, which accounts for more than 95% of world production (estimated to be about 1.5 to 2.0 million tonnes in 2002). The crop is most important in China (*c*. 600 000 ha, 1.3 million t), India (60 000 ha, 430 000 t), Vietnam (35 000 ha), Thailand (27 000 ha), Bangladesh (12 000 ha) and Nepal (3000 ha). There is also interest in Australia (2000 ha), the Philippines (a very small area) and Indonesia (planted area not specified). Most of the fruit is sold fresh, although some of the fruit produced in China and Vietnam is dried. A limited amount of fruit is canned and processed. Although large orchards exist in China (>10 000 trees), the majority of the crop throughout Asia is produced by smallholders with fewer than 100 trees. Despite the small number of trees,

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[1] By M.K.V Carr and C.M. Menzel

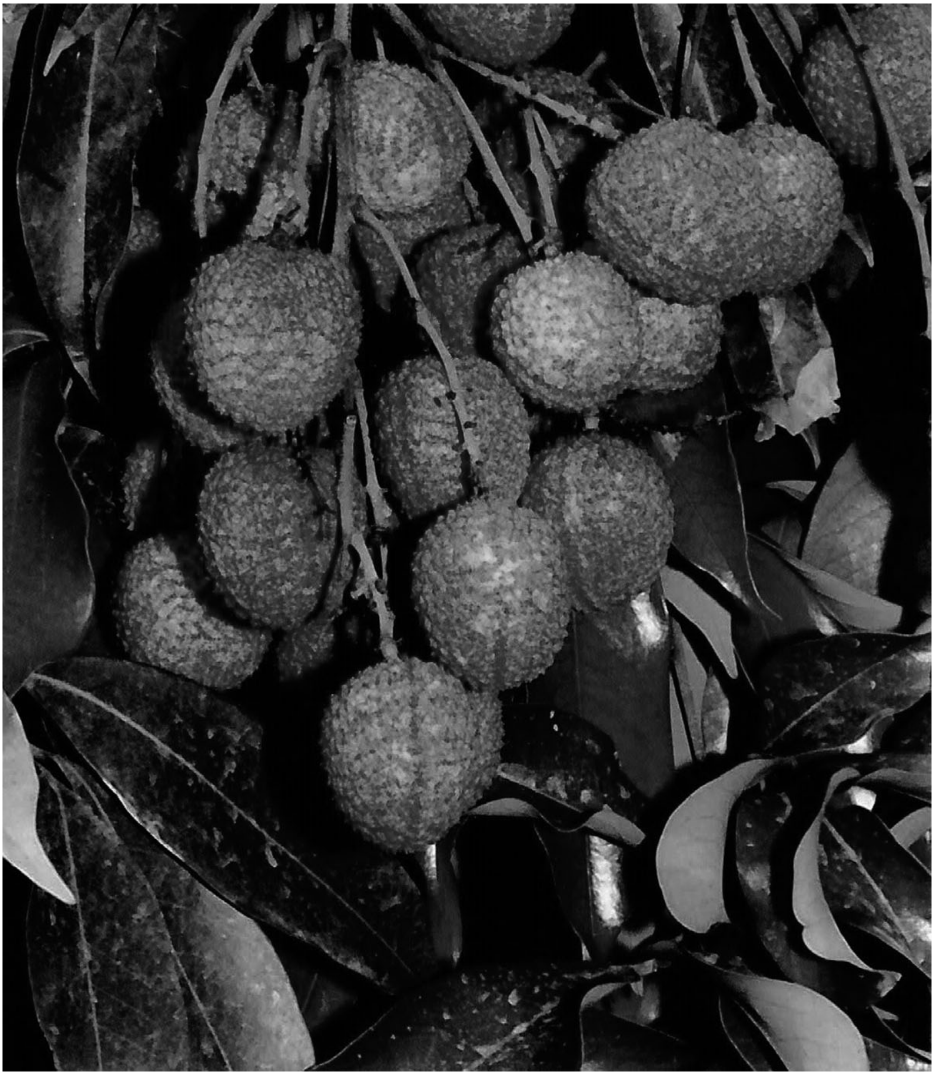

Figure 6.1 The outside of the lychee fruit is covered by a pink-red, rough rind that is inedible, but easily removed to expose the sweet, translucent white flesh – Israel (RS). See also colour plates section.

the revenue obtained from the sale of the fruit still makes a significant contribution to the income of relatively poor families (Papademetriou and Dent, 2002). There are numerous cultivars. For example, over 400 are grown in China alone. However, only a dozen are commercially important across the different growing areas. It has been estimated that the industry in South China provides employment for about 500 000 people (Mitra and Pathak, 2010).

This chapter begins by describing the stages of crop development of lychee, and the effects of temperature and water on flowering. This is followed by reviews of plant–water relations, water requirements, productivity and irrigation systems. The topic was last reviewed by Menzel as a chapter in a monograph on lychee and longan edited by Menzel and Waite (2005). Menzel (2002a) described in detail the lychee industry in Asia and the Pacific, and included a section on water and nutrition management.

Crop development

Much of the research reported in this section was concerned with explaining how temperature and water deficits influence flowering, using potted plants in controlled environments. Stern and Gazit (2003) have reviewed reproductive biology, and there are several chapters on the topic in the book edited by Menzel and Waite (2005).

Vegetative growth

Lychee is a medium-to-large, evergreen tree, with a short, stocky trunk and a low, large canopy. It is propagated commercially by air-layering (marcotting). It grows to a height of 10 m or more. The leaves are a lustrous deep green on the upper surface and a waxy lighter green (glaucous) on the lower surface. Shoot extension is characterised by a series of vegetative growth flushes in which the stem elongates and new leaves expand to full size over a period of several weeks. Shortly after leaf expansion, the terminal bud becomes dormant, whilst the leaves continue to accumulate chlorophyll and become more structurally rigid (O'Hare, 2002). Shoot growth is very sensitive to water deficits, which affects leaf production, stem extension and shoot dry weight. Temperature determines whether new shoots develop as leaves or flowers (Menzel *et al.*, 1989).

Flowering

Poor and erratic flowering is universal and results in low and irregular yields. As a consequence, the complexity of flowering has been the subject of detailed studies (Menzel, 1983; Menzel and Simpson 1991, 1992, 1995). Flowers grow on a terminal inflorescence formed on current shoot growth. The inflorescence consists of many branches, growing in clusters of ten or more, each holding hundreds of small white, yellow or green flowers that are distinctively fragrant. There are three main types of flower: male; hermaphrodite, functional female; and hermaphrodite, functional male. All three classes of flower are borne in the same inflorescence. The flowers are usually pollinated by insects (Pandey and Sharma, 1989), although wind-pollination can also play a part.

Initiation and development of the floral buds occur during winter, leading to anthesis in spring. A water deficit prior to floral induction may improve flowering by delaying new growth until cool weather arrives. The important role of temperature on vegetative growth and flowering was demonstrated by the results of experiments undertaken in Australia (Menzel *et al.*, 1989). Plants of cultivar 'Tai So'[1] were grown at different combinations of day/night (shoot), and root temperatures, and leaf water potentials. Flowering was very weak when daytime shoot and root temperatures were above 20 °C. Water deficits did not induce flowering when the plants were grown at high temperatures. The plants grown at low temperatures did not flower until they were re-watered. The plants grown at high temperatures never flowered.

Later, Menzel and Simpson (1990a; 1990b) compared the responses of seven cultivars to temperature. At day/night temperatures of 25/20 °C and 30/25 °C the trees grew, but did not flower. All the terminal shoots on all the cultivars produced inflorescences at 15/10 °C, but increasing the temperature to 20/15 °C increased the proportion of shoots that were vegetative and reduced the proportion of shoots that were floral. Constant root temperatures had similar effects on flowering: warm temperatures (27.5 °C) reduced or eliminated flowering compared with cool temperatures (15 or 12.5 °C).

Water deficits reduced vegetative growth, but had no direct effect on flowering. For example, at day/night temperatures of 30/25 °C, vegetative growth was reduced with a pre-dawn leaf water potential of -1.0 MPa, compared with growth in plants with a leaf water potential of -0.6 MPa. Plants with a constant leaf water potential of -2.0 MPa did not grow at all. When the droughted plants were watered after seven weeks and maintained at day/night temperatures of 30/25 °C, all the terminal buds grew out as leafy shoots. In contrast, when the plants were transferred to 15/10 °C all the terminal buds flowered (Menzel and Simpson, 1990b).

In a controlled environment experiment with potted 'Tai So' plants in Queensland, Australia, O'Hare (2002) showed that both temperature and the age of shoot influenced differentiation. A combination of mature shoots and low temperatures (15/17 °C day/night or 18/13 °C) resulted in good flowering. At high temperatures (23/18 °C), the age of the flush had no effect on shoot differentiation, and only vegetative shoots were produced.

In a follow-up study, O'Hare (2004) showed that root temperature had a direct effect on shoot development. At day/night temperatures of 18/13 °C, the period between successive flushes was five weeks, but at temperatures of 20 °C this was reduced to three weeks. There were no flowers at a root temperature of 25 °C. At day/night temperatures of 23/18 °C, warming the roots increased the proportion of vegetative shoots, whilst at 28/23 °C all the shoots were vegetative.

In eastern Australia (28.9° S), Olesen *et al.* (2002) found that shoots remained vegetative if the mean air temperature during early flush development was above 17–19 °C, but were floral at lower temperatures. This was the case regardless of the number of vegetative flushes between pruning in the spring or early summer, and winter.

Batten and McConchie (1995) had previously demonstrated that floral induction occured in growing buds. Floral initials were visible 39 days (30 days for mango) after transferring potted plants from high to low temperatures. The longer the buds at the time of transfer, the fewer flowers that were initiated.

Stern *et al.* (1993) investigated the effect of water deficits on flowering of 'Tai So' and 'Floridan' over three years at two sites in Israel. Water deficits imposed for six weeks in autumn increased flowering and, compared with well-watered control trees, yield. Further experiments in Israel in which three drought treatments were compared with well-watered controls confirmed that water deficits can control vegetative growth and induce flowering in this environment with dry autumns (Stern *et al.*, 1998). It was recommended that growers in Israel apply only 50% of potential evaporation (E_{pan}) in autumn in order to improve productivity.

Menzel (2002a) suggested that water deficits could be used to control flushing patterns and improve flowering in localities with dry winters, such as India and Thailand; however, the timing and duration of the water deficit for success in these locations are not known.

In an interesting study, Chaikiattiyos *et al*. (1994) compared the effects of temperature and water deficits on floral induction in four tropical fruit trees. Temperatures below 25 °C for avocado, and below 20 °C for lychee and mango, were necessary for flowering, and could not be replaced by water stress. In contrast, flowering in lemon was mainly determined by water deficits, with day temperatures of 18 to 30 °C.

Fruiting

The outside of the lychee fruit is covered by a pink-red, rough rind that is inedible, but easily removed to expose the sweet, translucent white flesh. This edible portion of the fruit is an outgrowth of the seed stalk and is called an aril. It grows as the fruit develops until it completely envelops the seed in most cases. The number of fruit maturing on an inflorescence varies from one to 40 or more (Storey, 1973). About 3% of the total carbon required for fruit growth over a season comes from photosynthesis by the fruit itself, and the remainder from the canopy (Hieke *et al*., 2002a).

The duration of each growth stage can be summarised as follows. After the fruit are harvested, vegetative growth occurs as a series of flushes lasting two to six months. Depending on the weather, inflorescences are usually formed after the completion of one or two vegetative flushes. The inflorescences usually take 6 to 12 weeks to develop before the first flowers begin to open. Fruit set occurs in the spring, and lasts two to four weeks. Fruit matures 11–16 weeks after anthesis (Menzel and Simpson, 1994a). Although orchards can yield up to 15 t ha^{-1} of fresh fruit, most orchards yield less than 5 t ha^{-1}.

Water deficits occurring before fruit set reduce the number of fruit on each inflorescence (Menzel, 2005). Water deficits after fruit set reduce the weight of individual fruit, mainly due to the production of smaller arils, which account for 65–75% of final fresh weight. Water deficits also induce fruit splitting.

Roots

Marler and Willis (1996) monitored root and stem extension of young ‘Tai So’ trees planted in six root observation chambers filled with sand, in Florida. There were four flushes during the year, with the amplitude and duration of each flush varying in the different replicates. Root extension was highly variable over time and between replicates. The mean maximum rate of absolute root extension was 7.4 mm d^{-1}, and that for stem extension 13.1 mm d^{-1}. There was no relationship between the timing of root and stem extension growth at this site over the year.

By contrast, O’Hare and Turnbull (2004) found that root growth in potted ‘Tai So’ trees alternated, on the whole, with shoot extension, regardless of the temperature. At all three day/night temperatures (18/13 °C, 23/18 °C and 28/23 °C) shoot buds emerged after a similar amount of root growth had occurred. Root growth was slow during bud break and early shoot extension, and to a lesser extent during chlorophyll formation in the new leaves. It was suggested that these were times when the shoots were a stronger ‘sink’ for assimilates than the root. Competition for assimilates during flower formation could also explain why root extension declined to negligible levels just prior to anthesis, before resuming again.

Menzel *et al.* (1990) investigated the distribution of roots of eight-to-ten-year-old ‘Tai So’ trees on five acid soils in Queensland (27° S). Soil samples were taken at 0.10 m intervals down to 1.0 m only, and the roots separated. The depth of rooting was greatest in clay soils, while the greatest root density was recorded in sandy soils. Eighty per cent of root dry mass was found within 0.20 m of the soil surface at one site, within 0.40 m at two other sites and within 0.60 m at the remaining sites.

There is indirect evidence of the effective depth of the roots based on the extraction of soil water during the dry season. For example, in South Africa, 10-year-old trees extracted water to at least 1.5 m, the limit of measurement (Menzel *et al.*, 1995). Similarly, eight-year-old trees extracted water to below 2 m in northern New South Wales, Australia (28° S) (Batten *et al.*, 1994).

Summary: crop development

1. Lychee is a medium-to-large evergreen, subtropical tree. Fruiting only occurs in the tropics at altitudes above 300 m.
2. Shoot growth occurs as a series of flushes with the rate of shoot extension related to temperature.
3. Flowering occurs when new shoots only a few millimetres long are exposed to temperatures below 20 °C.
4. Water deficits can affect the pattern of shoot development, but have no direct effect on floral initiation.
5. Flowers grow on terminal inflorescences formed on the current season’s growth.
6. Anthesis occurs in spring, and fruit mature in late summer and early autumn.
7. Poor and erratic flowering contributes to low and irregular fruit yields.
8. The edible part of the fruit is an appendage of the seed stalk, known as an aril.
9. Water deficits during flowering reduce fruit set, whilst water deficits after fruit set reduce fruit weight.
10. Water deficit can be used to control the pattern of shoot growth and improve flowering in localities with dry winters.
11. Roots can extract water down to at least 2 m in some soils.

Plant–water relations

Fundamental research on the plant–water relations has been conducted in several subtropical regions, including Queensland and New South Wales in Australia, South Africa, China and Israel. Three of these countries are new entries to the lychee industry.

Stomatal conductance and plant water status

In Queensland, Australia (27° S) Menzel and Simpson (1986) found that the amount of solar radiation intercepted by a leaf varied considerably depending on: (1) the aspect (north, south, east or west) of the tree being sampled, (2) the time of day and (3) whether or not the leaf was within the canopy or on the outer surface. These differences influenced the leaf temperature and hence the vapour pressure gradient between the leaf surface (stomata are only found on the lower surface) and the surrounding air. As a result leaf water potential (ψ_l) values in exposed leaves were below those recorded deeper in the canopy or facing away from the sunny side. Interior leaves on the south side of the tree were identified as the best indicator of the water status. Measurements over a six-day period during the dry season on irrigated 'Bengal' trees showed that ψ_l declined during the morning, reaching minimum values of about -1.0 MPa by 1000 h. Recovery to early morning values was not complete by sunset.

Following the publication of this paper it was recognised that the conductance measurements made at the same time as those for leaf water potential were subject to error due to dew on the leaves just after sunrise.

Batten *et al.* (1992) studied diurnal changes in stomatal conductance (g_s) and ψ_l on irrigated trees of two cultivars over a period of six months in north-eastern New South Wales (28° S). 'Bengal' had much higher conductances than 'Kwai May Pink', especially in winter. In addition, leaf water potentials at midday were lower (more negative) in Bengal. Calculated values of 'whole plant conductance' indicated that lychee has a relatively efficient water transport system.

In Israel, Stern *et al.* (1998) monitored diurnal changes in leaf and stem water potential (ψ_s). Midday stem water potential was more sensitive to irrigation treatments than leaf water potential. Minimum values of ψ_s occurred at around midday in both well-watered trees (-1.3 MPa) and severely stressed trees (-2.8 MPa). In an analysis of diurnal changes in ψ_l in 'Bengal' and 'Tai So', Menzel, and Simpson (1986) found that 85% of its variation during the day could be explained by changes in the saturation deficit of the air, the driving force for water loss from the leaf.

In north-eastern New South Wales, Batten *et al.* (1994) monitored changes in the water relations of eight-year-old 'Bengal' trees from one month before flowering until harvest. Selected trees were well-watered or left unirrigated and protected from rainfall with a plastic sheet on the ground surrounding the tree. Pre-dawn ψ_l in the unirrigated trees declined from about -0.3 MPa at the start of the experiment to -0.9 MPa at harvest. Minimum midday values in the control trees were about -1.0 to -1.1 MPa in May, when evaporation (E_{pan}) was low (2 mm d^{-1}). These values decreased to -1.7 to -2.0 MPa in December, when E_{pan} was 6–7 mm d^{-1}. In the unirrigated trees, midday values fell to -2.2 to -2.4 MPa.

Measurements of gravimetric soil water content showed that by December (mid-summer), water was being extracted in the 'dry' plots to depths of about 2 m in the clay loam (Batten *et al.*, 1994). The soil water content at this time was equivalent to a soil water potential of -1.0 MPa. The estimated potential soil water deficit (the difference between potential evapotranspiration and effective rainfall) in the unirrigated plots, where rainfall was excluded, exceeded 500 mm at harvest. Despite the low leaf and soil water potentials in the droughted trees, g_s only declined by 20% compared with values observed in the control trees.

A similar study carried out in South Africa (25° S) by Menzel *et al.* (1995) achieved slightly different results. One group of trees was irrigated weekly from late July until January (wet), while another group was left unirrigated through the dry season (dry). Plastic sheets were placed under the trees to help prevent rainfall soaking into the 'dry' plots. There was very little rain until after harvesting in January. Pre-dawn leaf water potentials in the controls were about -0.2 MPa compared with -0.4 to -0.8 MPa in the dry trees. In the afternoon, the corresponding minimum values were -1.7 to -2.1 MPa and -2.2 to -2.8 MPa, respectively. Maximum values of g_s occurred at 0700 to 0800 h in the controls. It then declined by about 50% by the middle of the day. Sometimes there was a slight recovery in the late afternoon. On average, values of stomatal conductance in the droughted trees were about half those in the control trees. Net CO_2 assimilation (A) generally followed the same pattern as g_s. Stomatal conductance in droughted trees was about half of its maximum value at ψ_l of -2.0 MPa, and decreased to one quarter when ψ_l declined to -2.5 MPa. Once the droughted trees were re-watered, ψ_l recovered within a week, whereas g_s and A had not fully recovered after five weeks. This is not uncommon. Depending on the severity and duration of the water stress, stomata of other species may also take some time to recover once the stress is relieved, even though leaf water potential may revover rapidly (Jones, 1992).

Roe *et al.* (1995) also found that gas exchange in droughted trees took ten days to return to pre-drought levels upon re-watering. They used a complex series of pot experiments to test if the results obtained were relevant to trees growing in the field. They concluded that results from potted plants are not always applicable to trees in the field if the potted trees were dried too quickly or if they had never been droughted previously.

Gas exchange

In order to explore how best to scale-up results obtained from single leaves to whole trees, Lloyd *et al.* (1995) measured the diurnal patterns of carbon dioxide and water vapour exchange in 'Gee Kee' and 'Haak Yip' enclosed in whole-tree, gas-exchange chambers. Over two five-day periods in north-eastern New South Wales (28° 29′ S), g_s and A were higher when photon flux densities (PFD) were above about 500 µmol m^{-2} s^{-1}, under overcast, as opposed to clear sky, conditions. Stomatal conductance increased with increases in the leaf temperature over the range 10 to 32 °C, before declining rapidly at higher temperatures. It declined exponentially as the saturation deficit increased from 0 to 4.0 kPa, and plateaued at irradiances above 500 µmol m^{-2} s^{-1}. By modelling the individual processes, Lloyd *et al.* (1995) were able to show that higher assimilation rates under lightly overcast conditions were not only a consequence of lower leaf temperatures and saturation deficits of the air, but also due to a more uniform distribution of irradiance across the canopy surface. The results of measurements made in the chambers were similar to those made on individual leaves in a laboratory (Batten *et al.*, 1992).

Chang and Lin (2007) studied gas exchange of trees grown in central Taiwan, under both controlled (24° N) and field conditions (21° N). Maximum A occurred when the PFD was above 800 μmol m^{-2} s^{-1}, leaf temperature was from 27–32 °C, and saturation deficit was below 0.7 kPa. Net assimilation and stomatal conductance declined when the saturation deficit exceeded about 2.0 kPa. By contrast, transpiration increased until the saturation deficit reached 2.5–3.0 kPa, before declining. Net CO_2 assimilation, stomatal conductance and transpiration were higher on well-exposed young leaves adjacent to fruit, than on shaded older leaves not adjacent to fruit. This may be due to both the higher light levels and the increased demand for photosynthates by the fruit. These two factors were not separated in this study.

In Shenzhen, China, Song *et al*. (2007) monitored diurnal changes in A of 17-year-old 'Nuomizi' trees in both well-watered and moderately droughted trees. The shape of the diurnal photosynthesis curves varied slightly with the season. There was a strong correlation between A and g_s in wet soil ($r^2 = 0.76$), and a weaker correlation when the soil was dry ($r^2 = 0.44$).

Hieke *et al*. (2002b) studied the effect of sunlight on leaf gas exchange and leaf expansion in potted seedlings and field grown plants in Queensland, Australia (27° S). Photosynthesis in individual leaves was saturated at about half full sun (PFD of 1200 μmol m^{-2} s^{-1}) and maximum leaf expansion occurred at higher irradiance levels (PFD of 2200 μmol m^{-2} s^{-1}). Improvements in canopy management techniques that maximised light interception and distribution were expected to increase the yield of lychee orchards.

Responses to drought

Tang *et al*. (2010) reviewed some of the physiological responses of lychee to drought. In a comparison of two contrasting genotypes, they found that the decrease in leaf relative water content (RWC) was less severe in drought-resistant 'Dongliu 1' than in drought-sensitive 'Chenzi'. This may have been because the integrity of the cell membrane and of the chloroplasts were maintained for longer in 'Dongliu 1'. Similarly, the abscisic acid content of leaves increased more in 'Dongliu 1' during a drought than in 'Chenzi'. Midday stem water potential was considered to be the best indicator of tree water status. The authors concluded that responses to drought recorded in field experiments were likely to be different from responses recorded in pot experiments.

Summary: plant–water relations

1. Leaves within the canopy on the south side of the tree best reflect tree water status.
2. Stomata are only found on the lower leaf surface (and on green fruit).
3. In well-watered trees, stomatal conductance typically peaks early in the morning, and then declines. Sometimes there is a slight recovery later in the afternoon.
4. Pre-dawn leaf water potentials are generally between −0.2 and −0.3 MPa in well-watered trees and decline to −0.9 MPa in droughted trees.

5. In well-watered trees, the midday values of leaf water potential range from −1.1 MPa, when evaporation is low, to −2.0 MPa when evaporation is high. For droughted trees the corresponding values are typically −2.2 to −2.8 MPa.
6. The stomata are fully closed at leaf water potentials of −1.1 to −2.8 MPa, depending on experimental conditions.
7. There is a close relationship between net CO_2 assimilation and stomatal conductance.
8. Maximum values of stomatal conductance occur at 27–32 °C, and decline rapidly as the saturation deficit of the air increases.
9. Peak rates of net CO_2 assimilation occur when photon flux densities are 500–800 $\mu mol\ m^{-2}\ s^{-1}$, and are greater on overcast days than on clear, sunny days.
10. When droughted trees are re-watered, it takes several days for gas exchange to return to normal values.

Crop water requirements

Very little work has been published on the water requirements of lychee.

In South Africa (25° S), Menzel *et al.* (1995) measured changes in volumetric soil water content during the dry season in irrigated and unirrigated 10-year-old ‘Tai So’ trees spaced at 10 × 10 m. After 16 weeks, the unirrigated trees had depleted water to a depth below 1.5 m. This was equivalent to a soil water deficit of 126 mm. The pattern of water extraction at that time was as follows: 28% from the soil surface down to 0.30 m, 23% from 0.30 to 0.60 m, 17% from 0.60 m to 0.90 m and 13% from 1.20 to 1.50 m. Water use in the well-watered plots (ET_c) averaged 26±1 mm $week^{-1}$. By comparison, evaporation from a USWB Class A evaporation pan (E_{pan}) ranged from 20 to 70 mm $week^{-1}$. The crop coefficient ($K_c = ET_c/E_{pan}$) was between 0.4 and 1.2, with no seasonal trend. However, ET_c declined as E_{pan} increased, as shown by the following equation:

$$K_c = 0.366 + 3.048\ \exp(-E_{pan}/16.147)\ (R^2 = 64\%; P < 0.001)$$

A common recommendation is to estimate reference crop evapotranspiration (ET_o), either from an evaporation pan or by using the Penman–Monteith equation. These data are then used to estimate ET_c with the appropriate crop coefficient (K_c).

In the northern Thailand highlands, Spohrer *et al.* (2006) attempted to specify the plant parameters needed to model water use in seven-year-old trees. They were able to predict successfully canopy interception of rainfall with a modified model, but were unable to determine universally applicable values for K_c. If direct measurements of E and T were not possible, the recommended values for K_e (the potential evaporation coefficient) were 0.6 for the ground area beneath the tree canopy, and 1.6 for the open area between the trees. This is an exceptionally high value. For estimating potential transpiration only, the value for K_c suggested was 0.8. The results of the experiments in South Africa (Menzel *et al.*, 1995) suggest that this approach over-estimates potential water use at times, and under-estimates potential water use at other times.

In Florida, USA, when there are no locally derived values, the monthly mean crop coefficients (K_c) recommended to lychee growers, over a year beginning in January, are as follows (Kisekka *et al.*, 2010a):

$$K_c = 0.40, 0.40, 0.90, 1.20, 1.20, 0.85, 0.85, 0.40, 0.40, 0.40, 0.40, 0.40(\text{December}).$$

These values are based on work conducted in South Africa by Menzel *et al.* (1995) using an evaporation pan. The authors do not indicate how these recommendations were estimated. There have been no studies to determine whether the relationship between water use and evaporation from an evaporation pan developed in a dry environment is applicable to trees growing in a humid environment such as Florida.

Summary: crop water requirements

1. Very little research on this topic has been identified.
2. In one study, the crop coefficient varied between 0.4 and 1.2 × E_{pan}, and declined as potential evaporation increased.
3. In South Africa, ET_c rates for mature trees averaged about 3.7 mm d^{-1} and in Queensland, Australia up to 4.5 mm d^{-1}.

Water productivity

In this section, the effects of water deficits and irrigation on crop productivity are considered. Menzel (2005) has summarised the results of research undertaken in West Bengal, India by Hasan and Chattopadhyay (1990; 1992). The irrigation treatments selected were based on different levels of depletion of the available water (30, 45 and 60%), together with an unirrigated control. Unfortunately, the soil depth within which the available soil moisture was calculated was not specified. Actual water use, referred to as 'consumptive use', was determined by gravimetric sampling. The best yields obtained over the two years the experiment operated appear to be from the treatment irrigated most frequently (30% depletion). The differences between all three irrigated treatments were small, but each of these out-yielded the control by up to 32 kg fruit $tree^{-1}$ (41 compared with 73 kg $tree^{-1}$). Water productivities (yield of fresh fruit divided by water use) were presented, although it is was not made clear whether water use was calculated for the whole year or just the irrigation season. The authors cited water productivities equivalent to 1.1–1.2 kg m^{-3}.

Irrigation experiments were also undertaken in Australia, South Africa and Israel, but only those in which the yields were recorded are considered here. Some of these experiments have already been described in the section on plant–water relations.

In northern New South Wales, the effect of a drought that lasted for a total of seven months, from one month before flowering to harvest, was unexpected (Batten *et al.*, 1994). The total number of fruit harvested from each inflorescence was 90% higher in the unirrigated trees (23) than in the irrigated trees (12). This may have been associated with reduced shoot growth in the droughted trees. The drought also reduced the fresh weight of individual fruit from 21.3 g to 19.6 g, mainly due to a reduction in the weight of the flesh. The yield per tree was not recorded. The effect of drought on productivity will depend on the relative effects on the growth of the fruit and on the growth of the shoots. In this example from New South Wales, the fruit were favoured over the shoots. It was a deep clay soil. A drought earlier or later in fruit development may not have given the same response. Drought can assist fruit development and reduce tree size in stonefruit through a similar mechanism (less shoot extension).

In a similar experiment in South Africa, water was withheld from trees from just before emergence of the inflorescences until four weeks after harvest (Menzel *et al.*, 1995). Water deficits reduced initial fruit set from 21.0±1.1fruit in an inflorescence to 14.1±1.8 fruit, and also the final set at harvest from 7.0±0.3 to 2.0±0.5 fruit. Many of the fruit in the droughted trees split before harvest. Water deficits did not alter the sigmoid pattern of fruit growth, but reduced yield from 51.4±5.5 to 7.4±3.3 kg tree^{-1}. It appears that these low-yielding trees experienced greater water deficits than the trees in Australia (Batten *et al.*, 1994). Any effect of the drought on shoot growth did not appear to benefit fruit production.

In Lower Galilee, Israel (32° N; alt. 200 m), Stern *et al.* (1998) studied the effects of irrigation during autumn on flowering and yield. This area normally has rainfall from November to April (long-term average *c.* 550 mm). Differential treatments were imposed on six-year-old ‘Tai So’ and ‘Floridian’ trees. The trees were droughted for about 40 days beginning at the end of the second vegetative flush, following harvest in the previous July. The four irrigation treatments had different levels of replacement of potential water loss (ET_c). The target applications were 100% (well-watered, the control), 50%, 25% or 0% ET_c (rainfall only). Potential tree water use was calculated by multiplying evaporation from a USWB Class A evaporation pan by a crop factor (K_c). To match increases in tree size, K_c was increased from 0.3 to 0.8 over the two years of the experiment. During the two-month interval between harvest and the start of the treatments, K_c was kept at 0.5. The 0.8 m-deep soil profile was clay, overlying basaltic rocks.

The total amounts of irrigation applied before the drought were 540 mm and 700 mm in 1994 and 1995, respectively. In 1994, 155 mm were applied to the control plots and in the following year, 120 mm. To prevent the trees from dying, some water was applied to the ‘dry’ treatment: 21 mm in 1994 and 7 mm in 1995.

Shoot extension was restricted in all the droughted trees. Flowering, judged visually on a scale of 0 (no flowers) to 4 (full flowering) was least in the control plots (score of 1.5 versus scores of about 2.5 in the other treatments). Both cultivars responded in the same way. The control trees had the lowest yields, about half that of the 50% ET_c treatment in 1994, and about one-third less in 1995. Yields from these treatments for ‘Floridian’ were about 4 kg tree^{-1} and 8 kg tree^{-1} in 1994, and 7 kg tree^{-1} and 12 kg tree^{-1} in 1995, respectively. The corresponding yields for ‘Tai So’ were 3 and 6 kg tree^{-1} in 1994, and 14 and 21 kg $^{\text{tree}-1}$ in 1995. The plant density was 500 trees ha^{-1}.

These results suggest that reducing water applications by about half before flowering can increase yields under these conditions. The response to higher levels of water deficit was mixed. In the first year, the yields of trees given 0 to 50% × ET_c were similar. However, in the second year the yields from trees given virtually no extra water were lower. Severe water deficits before flowering can reduce yields.

Summary: water productivity

1. The responses to irrigation depend on the growing environment, the level of the water deficit, the stage of growth and the time of floral initiation.
2. A moderate water deficit (replacing 50% of the water use) before floral initiation can increase flowering and yield in areas with low rainfall after harvest.
3. A moderate water deficit can increase fruit retention, but that may occur at the expense of final fruit fresh weight.
4. A severe water deficit after flowering can reduce fruit set and yield and increase the risk of fruit splitting.
5. Because of these complexities, water productivity has yet to be quantified across a range of environments.

Irrigation systems

Supplementary irrigation

Menzel (2002a) recommended that all new plantings should be irrigated if possible. Following his review of the results of field experiments in India, Australia and South Africa, Menzel (2005) concluded that well-grown, lychee trees are relatively drought tolerant. Trees can extract water at considerable depths (at least 1.5 m) in most soils and produce acceptable yields without rainfall or irrigation for several weeks. Irrigation every two weeks for a sandy loam, and every three to four weeks for a clay soil, in both cases returning the soil profile to field capacity, is recommended. Trees growing on poorer soils require more frequent irrigation.

Menzel (2005) believed that supplementary irrigation was likely to be advantageous in Australia, Hawai'i (USA), India, Israel and South Africa. However, in South-east Asia, including China, Thailand and Vietnam, the value of irrigation had yet to be quantified. Menzel (2005) included monthly totals of rainfall and evaporation, together with the potential irrigation need (evaporation minus rainfall) for seven international sites: Guangzhou, China, 23° N, annual rainfall 1700 mm, with the cumulative annual water deficit close to zero; Nelspruit, South Africa (25° S), 800 mm, deficit *c.* 1000 mm; Galilee, Israel (32° N), 600 mm, *c.* 1300 mm; Astonville, Australia (29° S), 1900 mm, *c.* 300 mm; Bundaberg, Australia (25° S), 1000 mm, *c.* 800 mm; Cairns, Australia (17° S), 2000 mm, *c.* 200 mm and Mareeba, Australia (17° S), 900 mm, *c.* 400 mm. The responses to irrigation will, however, vary depending on local conditions, in particular rainfall distribution and variability from year to year.

Irrigation methods

Drip or sprinkler irrigation is popular amongst wealthy farmers. Drip irrigation is also finding favour in India, although basin and flood irrigation still predominate. Irrigation is recommended during fruit development, whereas a drought before the normal time of floral initiation can improve flowering. For young trees irrigation at two- to five-day intervals is recommended. It is claimed by Singh and Babita (2002), but without supporting data, that irrigation on alternate days beginning six weeks before harvesting improves fruit retention, encourages better fruit development and minimises cracking of the fruit in India. In Australia, many orchards are irrigated two to three times a week. This is thought to be excessive, since a longer cycle is adequate (Menzel, 2002b). In the Philippines, irrigation of lychee is uncommon (Sotto, 2002). In Thailand, water sprayed from boats is a common method of irrigating trees growing on raised beds (Figure 6.2).

Figure 6.2 Water sprayed from small boats is a common method of irrigating crops growing on raised beds in Thailand (HDT).

There is no irrigation in the northern hilly areas of Thailand due to the topography. Modern orchards there have switched from flood irrigation to mini-sprinkler systems, sometimes with fertigation (Sethpakdee, 2002). In Vietnam, water resources are not easy to exploit in the hilly areas where the lychee is grown, and since there is adequate rainfall in the spring and autumn, supplementary irrigation is not practised (Hai and Dung, 2002).

Irrigation scheduling

Stern *at al*. (1998) attempted to find a reliable indicator of soil or tree water status that could be used to schedule irrigation during the autumn. Tensiometer readings of soil water potential were too variable to be useful. The best measure (least variable and most discriminating) was the midday stem water potential, with a critical or threshold value of -1.5 to -2.5 MPa, the exact value varying with the prevailing temperature and saturation deficit of the air.

In northern Thailand, Pinmanee *et al*. (2011) developed a low-cost irrigation control unit using tensiometers as the sensors, despite this experience of tensiometers reported by Stern *et al*. (1998). The control unit was made of cheap materials and, it was claimed, could be easily copied. No electricity is required.

In an on-farm experiment near Chang Mai in northern Thailand, four different methods of scheduling (drip) irrigation of 10-year-old trees were evaluated by Pinmanee *et al*. (2011). In the first, farmers were advised to turn the irrigation on when the soil matric potential, recorded on a tensiometer, fell below -40 kPa, and to turn it off when it increased to -20 kPa. The second treatment involved the farmer observing changes in the soil surface and in the appearance of the trees and making decisions on when to irrigate based on these visual clues. In the third treatment, the control unit was set to maintain the soil matric potential between -10 kPa and -45 kPa. In the final treatment, excess water was applied to the trees (total amount $= 4.8$ m^3 $tree^{-1}$). In the other three treatments, the amount of water applied was between 2.8 and 3.4 m^3 $tree^{-1}$. The corresponding yields of fruit were 29.2 kg $tree^{-1}$ (treatment based on manual readings of tensiometers), 36.7 kg $tree^{-1}$ (visual clues), 41.6 kg $tree^{-1}$ (control unit) and 23.7 kg $tree^{-1}$ (excess water). The resultant water productivities, based on irrigation water applied, were between 10.2 and 12.9 kg (fresh fruit) m^{-3} for the three scheduled treatments and 5.3 kg m^{-3}, where excess water was applied.

In Florida, Kisekka *et al*. (2010b) investigated the response of carambola (*Averrhoa carambola* L.) to different ways of scheduling irrigation. These experiments may have application to other tree crops, and could be used as a basis for future research in lychee. There were four treatments. Trees were irrigated based on real-time calculation of crop evapotranspiration, on historical estimates of crop evapotranspiration, with constant application rates at 76 mm $week^{-1}$ during the experiment or were left unirrigated. The trees irrigated on the basis of crop evaporation received 71 to 73% less water than those receiving the constant weekly rate. Yields ranged from 25 to 52 kg $tree^{-1}$, but the differences were not significant ($P > 0.05$), suggesting great tree-to-tree variability. These results confirm the potential that exists for saving water, and/or improving water productivity, by employing a science-based irrigation scheduling methodology, or by exploring the potential for deficit irrigation.

Summary: irrigation systems

1. There has been only a limited amount of research reported on the irrigation need of lychee, and virtually none in South-east Asia.
2. Limited information suggests that many orchards are over-watered.
3. Lychee is relatively drought tolerant and watering every two to three weeks is probably sufficient for most mature orchards.
4. In South-east Asia, topography and competition for water from summer-grown rice crops limit the opportunities for irrigation of lychee orchards.
5. Farmers use a wide diversity of irrigation methods, with micro-sprinklers and drip irrigation having the potential to be the most efficient.
6. Stem water potential at midday is a good indicator of tree water status, but has not yet been used in commercial orchards.
7. Changes in soil water content can be used to estimate tree water use, and is the preferred method for scheduling irrigation.
8. Opportunities exist to explore the possibility of improving the water productivity of lychee by applying less water.

Conclusions

Lychee is well established as an important fruit-tree crop in South-east Asia, but has only relatively recently been introduced as a commercial crop elsewhere. Erratic flowering, and poor and variable fruit set affect orchards planted in many producing countries. Most of the research on tree physiology and water relations of this species has been conducted in South Africa and Australia.

Several studies have shown the importance of temperature on flowering, whereas water deficits have no direct effect on the process. Drought can be used to control shoot growth and hence flowering in areas that have dry periods during autumn or winter. Similar data suggest that moderate droughts after flowering can increase fruit production, although these gains are at the expense of fruit size. Severe droughts at this time reduce fruit set and yield, and can lead to fruit splitting. Well-grown trees on good soils scan extract water down to 1.0 m or below. This reduces the need for frequent watering in commercial orchards. A watering every two to three weeks is probably sufficient for trees grown on sandy loams, and every three to four weeks on clays. Irrigation is best applied by monitoring changes in soil water levels. Further research is required to determine the benefits of irrigation in different growing areas, and the best way to apply the water.

Summary

The results of research into the water relations and irrigation requirements of lychee are collated and reviewed. The stages of plant development are summarised, with an emphasis on factors influencing the flowering process. This is followed by reviews of plant–water relations, crop water requirements, water productivity and finally irrigation systems. The lychee tree is native to the rainforests of southern China and northern Vietnam, and the main centres of production remain close to this area. In contrast, much of the research on the water relations of this crop has been conducted in South Africa, Australia and Israel, where the tree is relatively new. Vegetative growth occurs in a series of flushes. Terminal inflorescences are borne on current shoot growth under cool (<15 °C), dry conditions. Trees generally do not produce fruit in the tropics at altitudes below 300 m. Poor and erratic flowering results in low and irregular fruit yields. Drought can enhance flowering in locations with dry winters. Roots can extract water from depths greater than 2 m. Diurnal trends in stomatal conductance closely match those of leaf water status. Both variables mirror changes in the saturation deficit of the air. Very little research on crop water requirements has been reported. Crop responses to irrigation are complex. In areas with low rainfall after harvest, a moderate water deficit before floral initiation can increase flowering and yield. In contrast, fruit set and yield can be reduced by a severe water deficit after flowering, and the risk of fruit splitting increased. Water productivity has not been quantified. Supplementary irrigation in South-east Asia is limited by topography and competition for water from the summer rice crop, but irrigation is practised in Israel, South Africa, Australia and some other places. Research is needed to determine the benefits of irrigation in different growing areas.

Endnote

1 Also known as ‘Mauritius’.

7 Macadamia

Introduction

The macadamia nut (*Macadamia* spp.) is the only important commercial food crop indigenous to Australia, originating along the fringes of rainforests in coastal south-east Queensland and north-east New South Wales, between latitudes 25.5 and 29° S. For thousands of years before European settlement the aborigines ate the native nut (edible kernels[1]) that grew as an understorey species in the rainforests of eastern Australia (Figure 7.1). The first commercial orchard of macadamia trees was planted in the early 1880s in New South Wales, but it was not until the 1970s that the industry began to develop rapidly in Australia (Quinlan and Wilk, 2005). Macadamia was introduced into Hawai'i in 1892, where it was developed as a commercial crop from the 1920s (Pope, 1929). Beyond Australia and Hawai'i, macadamia is now produced commercially in South Africa, Brazil, Kenya, Guatemala and Malawi, as well as China, Thailand and Vietnam. All these countries are within latitudes 0–32° S and 0–34° N. Australia is the world's largest producer, with over 15 000 ha yielding about 40% of the estimated 90 000–100 000 tonnes of nut-in-shell (10% water content) produced globally each year.

Stephenson and Trochoulias (1994) have reviewed aspects of the environmental physiology of *Macadamia*, with an emphasis on irradiance, temperature and water stress. Huett (2004) reported on a field study in Australia of the impact of pruning and hedge management strategies on canopy photosynthetic performance, and reviewed the literature on physiological factors influencing orchard productivity. Hancock (1991) prepared a basic guide for macadamia production and research, with a focus on Malawi. More recently, Hardner *et al.* (2009) have reviewed the genetic resources and domestication of macadamia and Nagao (2011) has compiled a useful review of macadamia production, processing and marketing practices.

The main sources of advice to growers are derived from research in Hawai'i, South Africa and, in particular, Australia. The physiology of *Macadamia* spp. has been the subject of a great deal of research, but little has been reported on crop–water relations. The chapter begins with a description of the stages of crop development (including roots) in relation to water availability, followed by reviews of plant–water relations, water requirements, water productivity and irrigation systems.

Figure 7.1 Macadamia is the only important commercial food crop indigenous to Australia. It originated along the fringes of rainforests like these found in coastal north-eastern Australia (MKVC). See also colour plates section.

Crop development

Only two of the three *Macadamia* species are edible: the smooth-shelled *M. integrifolia* Maiden and Betche, and the rough-shelled *M. tetraphylla* L. Of these two, *M. integrifolia* is commercially the more important. It is distributed to the north of the zone (25.5–27.6º S) in Australia, where it originated, and within 24 km of the coast. Both species overlap in southern Queensland, where interspecific hybrids occur naturally (Nagao, 2011). *M. integrifolia* produces nuts with a ‘unique delicate flavour, a fine crunchy texture, and rich creamy colour’ (75–79% oil; 4.6% total sugar). They are marketed as raw in-shell nuts or as processed products (Stephenson and Trochoulias, 1994). Although macadamia is adapted to the fringes of the subtropical rain forests, its commercial development (and cultivar selection, including interspecific hybrids) has occurred in the more equitable climate associated with the islands of Hawai’i (20º N) (Pope, 1929). Species allocation has, until recently, been based on morphological traits, but it was not possible with this approach to quantify the proportional contributions of each species to an individual hybrid genotype. This is possible using DNA marker technologies. Many of the hybrids tested in this way have been found to contain a higher proportion of *M. tetraphylla* than was originally thought. Individual cultivars can now also be identified (Peace *et al.*, 2002; Peace *et al.*, 2004).

Despite macadamia being native to Australia, most of the commercial varieties grown in Australia (and elsewhere) have been (re)imported from Hawai’i. In order to facilitate future genetic improvement, it is important that existing wild populations of the species (under threat from land clearance) are conserved (Hardner *et al*., 2009). Stephenson (1990) has summarised the attributes of the principal Hawai'ian (usually with an HAES label) and Australian (e.g. Hinde, Own Choice, Renown and Maroochy) selections, whilst the aim of a current breeding research programme is to produce top performing Australian cultivars that are suited to local growing conditions (Wayne Hancock, personal communication).

Vegetative growth

The macadamia tree is usually propagated by grafting *M. integrifolia* onto seedling rootstocks of *M. integrifolia* or *M. tetraphylla*. Seedlings of hybrids and cuttings are also used. Economic yields are not produced until six or seven years after transplanting into the orchard, but once established, *M. integrifolia* may continue bearing fruit for over 100 years. The macadamia tree is evergreen and can reach a height of up to 20 m (Figures 7.2, 7.3 and 7.4). Growth occurs in a series of vegetative flushes. *M. integrifolia* leaves are arranged in whorls of three, with three buds in the axil of each leaf. Multiple branches (and inflorescences) may therefore be produced from each node (Stephenson and Trochoulias, 1994). Pruning and training are needed during the first three years after planting in order to produce a conical-shaped tree with a strong vertical central leader and scaffold branches (Figure 7.4). Cultivars differ considerably in the shape and structure of the tree canopy, making some susceptible to wind damage (Stephenson, 1990; Nagao, 2011).

Figure 7.2 The macadamia tree is usually propagated by grafting *M. integrifolia* onto seedling rootstocks of *M. integrifolia* or *M. tetraphylla* – Uganda (HDT).

Figure 7.3 The macadamia tree is evergreen and can reach a height of up to 20 m. Growth occurs in a series of vegetative flushes – northern New South Wales, Australia (MKVC).

Figure 7.4 Macadamia trees interplanted with coffee: note the water conservation pits alongside the coffee plants – Malawi (MKVC).

Macadamia trees grow at relatively low light levels. For example, 20% of full daylight is sufficient to support large numbers of new vegetative shoots, whilst 50% of flowers and fruit are produced in areas of the tree that receive less than 9% of full daylight (McFadyen, 2011). Variation in light distribution within the canopy leads to an uneven distribution of leaf and fruit and to a heavily shaded void in the middle of the tree. As a macadamia orchard matures, the nut yield to canopy ratio declines (this ratio is a measure of canopy efficiency), but, by delaying the time of pruning from the spring to early summer, nut yield can be increased by up to 15%. This is because the leaf flush cycle that follows a prune in the spring reduces fruit set. It also hastens the development of hardened wood on which the flowers form (Huett, 2004).

The response of macadamia to temperature has been the subject of detailed research in Australia. It appears to be the most important climatic variable affecting growth rates and productivity (Stephenson *et al*., 1986). The optimum air temperature for growth is within the range 20–25 °C, with a base temperature between 10 and 15 °C. High temperatures (>30 °C) cause chlorosis of new leaves, and multiple bud break followed by callusing and dieback of new growth (Trochoulias and Lahav, 1983). The crop can withstand mild frost (as low as −6 °C) for short periods (Stephenson, 1990).

In a detailed lysimeter-based study in Queensland, Stephenson *et al.* (2003) found that mild water stress (see below for details) suppressed vegetative growth/flushing, but upon re-watering there was a massive burst of leaf growth (recorded as a percentage of the total canopy surface). This flush can be delayed by several months. At the end of the experiment, stressed trees (cv. Keauhou (HAES 246)), 10-year-old) had a similar dry mass of foliage (26.5 kg tree^{-1}) to that of unstressed trees (24.5 kg tree^{-1}).

Flowering

In south-east Queensland, floral initiation occurs during the shortening days (day length 10 h 40–50 minutes) of early May (late autumn). The flower buds are then dormant for 60–96 days (depending on location and cultivar). Dormancy ends after a rise in temperature and some rain, with flowering concentrated in August and September (the following spring), 137 to 153 days after floral initiation (Moncur *et al*., 1985; Landsberg, 1988; Stephenson and Trochoulias, 1994).

In this region of Australia, differentiation of the inflorescence buds occurs when the night temperatures are in the range 11–15 °C. This is about 4–5 °C cooler than those experienced in Hawai'i. Warm nights at this stage of flower bud development (15–20 °C), when followed by low ambient night temperatures prior to anthesis (10–11 °C), extend the period of floral bud initiation to up to six months. In Hawai'i this is from late November to May. There can then be as many as three discernible flowering peaks (Stephenson and Gallagher, 1986a; Nagao, 2011). This response to temperature increases the number of flowers, but not necessarily the number of nuts per tree. In Malawi (16° S), there can be two flowering peaks, depending on altitude and season, with nuts at different stages of development during much of the year (Wayne Hancock, personal communication). In Brazil (21° S), flowering (white buds) begins (on six-year-old trees) during May, with anthesis in August and September (Sacramento and Pereira, 2003).

A single tree produces in excess of 10 000 inflorescences (pendulous racemes). These are borne on hardened wood within the leaf canopy. Each inflorescence has 200–300 flowers, of which only 5–10% set fruit. Nut set is enhanced by cross pollination. Water stress during flowering can cause the perianth (the outer part of the flower, containing stamens and carpels) to become desiccated, and pollination may then fail (Stephenson and Trochoulias, 1994, citing others). In one study, the timing, severity or duration of water stress during floral initiation had no consistent adverse effect on flowering intensity (except when it lasted for 60–70 days), although damage to the flower parts was observed (Stephenson *et al.*, 2003).

It is considered to be likely that macadamia flowers (through the sepals that are initially heavily pubescent, but glabrous at anthesis) contribute substantially to water loss during anthesis (Stephenson and Trochoulias, 1994).

Fruiting

In Hawai'i, the first period of abscission occurs during the two weeks following anthesis. This can mean the loss of 90% of the pollinated, but unfertilised flowers. The second period occurs three to eight weeks after anthesis and commonly involves the shedding of over 80% of the initial small fruit. The third period of abscission begins nine weeks after anthesis and lasts until the nuts mature about 30 weeks after flowering (Sakai and Nagao, 1985). Although between 6 and 35%[2] of the 300 or so flowers on each raceme set fruit, only 0.3% may reach maturity (Nagao, 2011). High temperatures induce premature 'nut drop' in the spring. The critical temperature, above which unacceptable yield losses occur, is about 30 ºC. The duration of temperatures like this, if they are to cause damage, has not been specified. But a considerable decline in nut retention was recorded within less than one and a half weeks of pot-grown trees being exposed to constant air temperatures of 25, 30 or 35 ºC (beginning one week after nut set) especially at low atmospheric humidity (Stephenson and Gallagher, 1986b;1987). Climate change could make this worse, especially at low altitudes.

The macadamia fruit is botanically classified as a follicle (it is not strictly a nut), in which only one of the two ovules develops. It takes six months to mature, after which the fruits are shed naturally (Figure 7.5). The quality of a fruit is related to its oil content (principally unsaturated fatty acids) and composition. It should contain at least 72% oil and have a specific gravity less than 1.0 (the higher the specific gravity the lower the oil content). Oil accumulation in the kernels is reduced if daytime temperatures exceed 25–30 ºC during the latter stages of nut development. Individual kernel weight may also be reduced if daytime temperatures exceed about 30 ºC (Stephenson and Gallagher, 1986c). Once-over harvesting is not possible due to the protracted flowering season and the extended maturation period. Harvesting occurs at approximately monthly intervals (Stephenson, 1990). According to Wayne Hancock (personal communication) water stress seems to affect the following year's crop more than the current year, except in years when there is a very serious drought.

Figure 7.5 The macadamia fruit is botanically classified as a follicle (it is not strictly a nut). It takes six months to mature, after which the fruits are shed naturally – Kenya (HDT).

As an example, the sequence of nut development stages in Malawi (16º S; alt. 600 m) is shown in Box 7.1. The rains last from November to May.

In a preliminary study in Queensland, a linear relationship between nut yield per tree and the surface area of the leaf canopy was established (sample size: 39 trees; $r = 0.90$) (Bell and Bell, 1983; Russell, 1985).

In South Africa, Allan (1972; 1983) used thermal time or day-degrees, summed above a mean daily base air temperature of 12.8 ºC, to identify regions suitable for macadamia production. He compared the seasonal (and growth stage) totals with those calculated for the areas of the world where macadamia originated and/or is successfully grown, namely: Australia (NSW, 2400 ºCday and Queensland, 2900 ºCday), Hawai'i (Kona, 2700 ºCday and Kau, 3400 ºCday) and Malawi (Naming'omba, 2800 ºCday and Bvumbe 2400 ºCday). This method of calculating day-degrees does not allow for the adverse effects of excessively high temperatures

Box 7.1 The sequence of nut development stages in Malawi (16° S; alt. 600 m)

Time of year	Development stage
● May	Floral initiation
● (June), July/August	Flowering
● August/September	Fruit set
● September/October	Early nut fill
● October to December	Late nut fill/shell hardening
● December to March	Oil accumulation
● January to April	Harvesting

(say >25 ºC). It is not known if this approach to the siting of macadamia orchards is widely used.

Roots

Whole-tree excavations, root core sampling and mini-rhizotrons were used by Firth *et al*. (2003) to quantify, in a very detailed study, the distribution and density of the root systems of macadamia trees at two sites in New South Wales. They described the root systems as being ‘relatively shallow and spreading’. Grafted 12-year-old orchard trees (cv. Keauhou (HAES 246) on *M. tetraphylla* rootstock) had a truncated tap root (only 0.6 m in length, probably due to damage when transplanted) with the lateral root framework and most of the fibrous roots all found within 0.40 m of the soil surface. By contrast, the taproot of seven-year-old, ungrafted *M. tetraphylla* seedlings was 1.2 m long, with branches at depth. The density of fibrous roots, which were ‘hardened and non-fleshy’, declined with depth and with distance from the trunk (for example, from 5.0 (±0.43) cm cm^{-3} at 0–10 cm depth to 1.7 (±0.45) cm cm^{-3} at 10–20 cm depth at 0.5 m from the trunk, and from 2.3 to 1.1 cm cm^{-3}, respectively, at 1.0 m distance). These values were similar to those obtained in earlier work in the same study area. Roots grew predominantly in the autumn, but new fibrous roots were produced in early winter and in the spring.

Dense clusters of rootlets, called proteoid or cluster roots, increase the surface area of the root system, enhancing nutrient and water absorption (Stephenson and Trochoulias, 1994). At the same two sites in New South Wales, proteoid roots were observed at 0.40 m depth (the limit of measurement) and appeared to retain their function for more than a year, even in relatively dry conditions. The presence of an established legume groundcover was associated with a higher proteoid root length density than that recorded under bare soil (Firth *et al*., 2003).

In Australia, large 15-year-old trees had roots extending to depths of at least 1.60 m in a deep sandy soil, whilst medium-sized trees had an effective root depth of 0.8–1.0 m in a clay loam (Newett, 1988). In Queensland, Stephenson *et al*. (2003) found that roots accounted for 28% of the total tree biomass of both stressed and unstressed trees (cv. Keauhou (HAES 246)).

Summary: crop development

1. Vegetative growth occurs in a series of flushes.
2. Variation of light intensity within a leaf canopy can lead to uneven distribution of the fruit: 50% of flowers are produced in areas of the canopy exposed to only 9% of full sunlight.
3. Mild water stress suppresses vegetative growth, but after re-watering a large flush can compensate for any previous loss.
4. Daytime temperatures in excess of about 30 ºC can be damaging. The minimum mean air temperature for growth is about 12–13 ºC; the optimum air temperature is about 25 ºC.
5. Less is known about the response of macadamia trees to atmospheric humidity (saturation deficit): no threshold value has been specified.
6. Floral initiation occurs in late autumn (but has been observed to occur earlier than this), with flowering in the following spring.
7. Depending on location, there can be up to three discernible flowering peaks.
8. Although a single tree can produce more than 10 000 inflorescences, only 5–10% of the flowers may set fruit, with as few as 0.3% reaching maturity.
9. The root system is 'relatively shallow and spreading'. An undamaged tap root can extend to a depth of >1.2 m, whilst a dense mat of fibrous roots occupies the top 0.40 m of soil.
10. Clusters of rootlets, known as proteoid roots, increase the surface area of the root system.
11. Roots can represent 28% of the total plant biomass.

Plant–water relations

Stomata are found only on the abaxial (lower) surface of the leaf, at densities of 360–500 mm^{-2}. The xeromorphic leaves have sclerified bundle sheath tissues, which are an adaptation for locations where there is periodic drought. The leaves do not have a wax coating and there is no pubescence (Stephenson *et al.* 1989; Stephenson and Trochoulias, 1994).

Diurnal changes in stomatal conductance and leaf water potential (ψ_l) were monitored by Lloyd *et al.* (1991) in irrigated and unirrigated macadamia trees in New South Wales. Conductance was low early in the morning, and reached a peak by 1200 h before declining during the afternoon. On a second occasion, when leaf temperatures reached 30 ºC, partial stomatal closure was observed during the middle of the day, followed by re-opening, and then progressive closure from 1600 h onwards. On the first occasion, minimum ψ_l values were reached by 1000 h and by 0800 h on the second occasion (about −1.1 MPa in irrigated trees and −1.2 MPa for unirrigated trees). After 0800 h, ψ_l remained relatively constant in both treatments until 1600 h, before increasing.

By contrast, in a lysimeter-based study in Queensland, stomatal conductances declined progressively from high values at 0800 h to low values at 1500 h, in both stressed and frequently irrigated trees (cv. Keauhou (HAES 246)), before recovering. This diurnal pattern was matched by changes in rates of photosynthesis. In well-watered trees ψ_l reached minimum values of -1.1 MPa but declined to -1.5 MPa in water-stressed trees. During the day, ambient air temperatures and saturation deficits increased from 15 to 18.5 °C and from 0.2 to 1.0 kPa, respectively (Stephenson *et al.*, 2003).

In a series of glasshouse experiments in Queensland with young potted trees under controlled conditions (day/night temperatures 28/21°C; daytime saturation deficit of the air 0.85 kPa), Stephenson *et al.* (1983; 1989) and Stephenson and Gallagher (1990) attempted to quantify the responses of three cultivars (Keauhou (HAES 246), Kau (HAES 344) and Keaau (HAES 660)) to water stress. Virtually complete stomatal closure occurred at a ψ_l of about -1.8 to -2 MPa, which corresponded to a relative water content of 86%. Zero turgor occurred when ψ_l reached -3.8 MPa, whilst mature leaves were permanently damaged at -5.0 MPa. Soft young leaves wilted at $\psi_l = -2.4$ MPa. Stomatal closure helped to maintain a favourable plant water status. The rapid rate of stress development, which is an unavoidable component of pot-grown trees, meant that there was no time for osmotic adjustment.

Field measurements taken over a dry season in New South Wales showed how stomatal conductance in unirrigated trees only began to decline, relative to irrigated trees, about three weeks after the rains had ended (Lloyd *et al.*, 1991). Subsequently, it took about 30 days after the rains began for these values to return to those of the well-watered trees. By contrast, daytime ψ_l remained the same for about eight weeks after the rains had ended and as the soil dried, before declining, but it recovered very quickly when the rains recommenced.

As part of the same project, Lloyd (1991), using data obtained under controlled laboratory conditions, developed a model to describe the changes in stomatal conductance and gas exchange of leaves of *M. integrifolia* that occur in response to changes in ambient weather conditions. According to this model, for a given temperature, the stomatal conductance declined exponentiallly as the dryness of the air increased (conductance was proportional to the inverse of the square root of the saturation deficit of the air). For a given irradiance level, conductance increased linearly with leaf temperature up to 30 °C and then declined. There was a very good linear relationship ($r^2 = 0.87$) between the conductance predicted by the model and 17 sets of field measurements taken over three days on five- to six-year-old irrigated trees. Incorporating leaf water potential measurements failed to improve the precision of the estimate (Lloyd *et al.*, 1991). There was, however, a strong relationship between ψ_l and the instantaneous transpiration rate. As a consequence, having used the model to estimate the stomatal conductance, Lloyd *et al.* (1991) developed an equation to predict the leaf water potential.

The hydraulic conductivity of the whole tree could then be calculated. Its value was found to be much higher than those reported for other horticultural tree crops. As stomatal closure also occurred without concurrent changes in ψ_l, Lloyd *et al.* (1991) argued that both these attributes would give the macadamia tree a competitive advantage in its native habitat. In addition, a high pre-dawn leaf water potential, even after four months without rain, suggested an efficient system for extracting water from the soil and its transfer through the root. All these processes could help to explain the apparent tolerance of macadamia to periodic dry conditions.

Photosynthesis in macadamia is depressed at high air temperatures (30–35 °C). For example, measurements reported by Huett (2004) showed how, on a sunny day in New South Wales, photosynthesis (and stomatal conductance) declined when the leaf temperature exceeded 36 °C and virtually ceased at 41 °C. The ambient air temperature was 32.5 °C.

In South Africa, intermittent sprinkling of macadamia alleviated heat stress through evaporative cooling of the leaf surface (by 5–8 °C) in hot environments (>30 °C), increased ψ_l and, for sun-exposed leaves, reduced stomatal conductances. Stem circumference and tree height were both increased, despite problems with the sprinkler control system, which prevented a season of treatments from being completed (Allan *et al.*, 1982; Allan, 1983; Stephenson and Trochoulias, 1994). Improvements in the control system, and further examples of the effect of leaf cooling on macadamia (a greater proportion of grade 1 kernels), were subsequently reported by Allan *et al.* (1994).

Summary: plant–water relations

1. Stomata only occur on the abaxial leaf surface.
2. Diurnal changes in stomatal conductance are matched by changes in rates of photosynthesis.
3. Stomatal closure occurs without concurrent changes in leaf water potential.
4. Full stomatal closure occurs at a leaf water potential of about −1.8 to −2.0 MPa.
5. Photosynthesis is depressed at air temperatures >30 °C.
6. Macadamia has several physiological and morphological attributes that help to explain its apparent tolerance to periodic dry conditions, as found in its native habitat.

Crop water requirements

According to Stephenson and Trochoulias (1994), drought often limits tree growth, as well as the set, retention, growth and quality of the nuts. The flowering and oil accumulation stages are particularly sensitive to water stress. Yields tend to be enhanced by irrigation in areas where relatively dry periods coincide with flowering and early nut development stages. But, as yield responses to irrigation are inconsistent, it is difficult to find published reports of experiments (with the exception of one by Stephenson *et al.* (2003)), to support these views.

The minimum annual rainfall for successful macadamia production is considered to be about 1000 mm, although high yields in Hawai'i were correlated with well-distributed rainfall often exceeding 2000 mm (Stephenson and Trochoulias, 1994, citing others). There is only one example of measurements of the actual water use (*ET*) of macadamia, which was undertaken in Queensland and described by Stephenson *et al.* (2003).

Large drainage lysimeters, measuring 3 m in diameter by 1.6 m deep, were used to monitor ET over a 12-year period from transplanting in 1983 to 1995. The trees (cv. Keauhou (HAES 246)), grown from cuttings to reduce genetic variability, were irrigated frequently until 1989, two years after coming into production, after which differential watering treatments were imposed (these are described below). Initially there were 24 lysimeters (some had to be excluded during the course of the experiment), each with one tree. The soil was described as sandy. Observations indicated that the growth of the trees, including roots, in the lysimeters was ‘normal’.

Over a season, *ET* averaged 75 L tree^{-1} day^{-1} (ranging between 52 L tree^{-1} day^{-1} in the winter up to 80 L tree^{-1} day^{-1} in the summer). In water-stressed trees water was extracted from soil depths >1.3 m, the limit of measurement, compared with 0.70 m for the unstressed (frequently irrigated) trees.

Summary: crop water requirements

1. Few attempts to measure the water use of macadamia trees have been reported.
2. In Nambour, Queensland the best estimates of daily *ET* rates are between 52 L tree^{-1} (winter) and 80 L tree^{-1} (summer).
3. Water is extracted from depths >1.3 m.

Water productivity

In Malawi, where there is an annual five-month-long dry season, Hancock and Banda (1991) commented on the difficulty and cost of macadamia irrigation experiments when the outcomes are often inconclusive. Whilst recognising that irrigation is necessary in the first few years after planting, they advocated for mature trees an analytical approach, using climatic and soils data, to assess the likely need for irrigation. For this purpose, they recommended, where weather data are incomplete, the Blaney–Criddle equation to estimate ET_o, a crop factor (K_c) $= 0.65$, 75% confidence limits for *ET* and rainfall (based on a minimum of 10 years of weather data), an effective rooting depth of 1.5 m, and easily available water equivalent to 75% of the total available water. They concluded that at sites in Malawi with an annual rainfall of over 1200 mm, at an altitude greater than 600 m, and with deep soils, irrigation of macadamia was unlikely to be justified. This work also indicated that a four-month-long dry season did not have a detrimental effect on yield. But, as the altitude decreased, with a corresponding increase in temperature, and as the length of the dry season increased, the impact of water stress was seen in premature shell hardening, leading to an increase in small nuts (variety 660) and leaf discolouration in some clones (508 and 333).

The cyclical and highly variable nature of macadamia yields (especially cv. Kau (HAES 344)) makes it difficult to establish cause and effect, and to quantify yield responses to water. According to Huett (2004), a minimum of five years is needed to demonstrate a response, even in well-designed and well-managed field experiments. Huett (2004) was particularly critical of a two-year irrigation trial in Australia, which failed to include a rainfall-only control treatment (Searle and Lu, 2002).

Only a few long-term experiments have been reported. In northern New South Wales (29º S), an irrigation experiment (duration eight years) failed to show any consistent effects of irrigation on yields (Trochoulias, 1988b). Varying depths of water were applied to single tree plots (there were four replications) of 8- to 16-year-old trees (cv. Keauhou (HAES 246)) from 1979 to 1987. The soil was a deep free-draining clay loam with an estimated available water capacity of 150 mm m^{-1}. Annual rainfall totals ranged between 1232 and 2283 mm. When evapotranspiration exceeded rainfall over a week, irrigation was applied with micro-sprinklers at five different rates (30 L h^{-1} up to 234 L h^{-1}), from flowering (August) to harvest (May). In addition, there was an unirrigated control treatment. Potential evapotranspiration was calculated as $0.75 \times E_{pan}$ (screened USWB Class A evaporation pan). A simple water balance was maintained from which the amount of water to apply was determined: two treatments received less water than needed, two received excess and one was close to the expected optimum. Annual quantities applied varied from as little as 213 mm up to 770 mm, applied in 9 to 24 irrigation events.

After allowing for the initial size of each tree (Figure 7.6), irrigation was found to have no significant effect on tree size or on nut-in-shell yield (which had reached 35 kg $tree^{-1}$ by 1987). As Huett (2004) has pointed out, the trees were grown at very low density (11 × 11 m; 83 trees ha^{-1}) and, by the end of the experiment, the crop cover was still only 37%. The roots probably extended beyond the limits of the crop canopy, thus increasing the volume of soil water available to each tree. Although irrigation reduced the individual nut-in-shell weight by up to 7%, the kernel weight as a

Figure 7.6 An immature macadamia orchard in northern Malawi. Note the variability in tree size. It is necessary to allow for the initial size of each tree when interpreting the results of irrigation experiments (MKVC).

percentage of this figure remained the same, regardless of treatment (*c*. 35%). Kernel quality as measured by the proportion of ‘floaters’ in tap water was slightly reduced by irrigation (3% fewer grade 1). Yields across all treatments averaged 900 g m^{-2} of leaf canopy (a measure of efficiency). The weather conditions experienced over the eight years were considered to be representative of long-term expectations. As a result of these findings, irrigation of macadamia was not recommended at this location (Trochoulias, 1988b; Trochoulias and Johns, 1992). Further north in the Gympie and Bundaberg regions of Queensland, Australia, where it is less wet, but warmer, irrigation is needed to support productivity (Wayne Hancock, personal communication). Irrigation is also needed in new macadamia-growing areas like Emerald in Central Queensland (R.A. Stephenson, personal communication).

In the lysimeter-based study in Queensland reported by Stephenson *et al*. (2003), and referred to above, water was withheld until the leaf water potential (pre-dawn) declined to −1.5 to −2.0 MPa at various growth stages. This value was maintained by partial water replenishment at two-day intervals. Yield responses to the stress treatments were variable from year to year (1991–1995). In one year, some of the stressed treatments gave yields more than or similar to the well-irrigated control treatment. When totalled over the five years, yields from trees stressed during floral development and, in particular, during the premature nut drop and nut maturation stages, tended to be lower (*c*. 40–53 kg $tree^{-1}$) than the control treatment (*c*. 73 kg $tree^{-1}$). With the exception of one year, stress during floral initiation had no effect on yield. Larger yields were generally, but not entirely, related to higher nut numbers. Water stress during the nut maturation stage, in particular, reduced the quality (kernel recovery) of the nuts. Reduced rates of photosynthesis at this time coincided with the critical oil accumulation stage.

Yield forecasting

In Hawai’i, Yamaguchi (2005) developed three linear crop models to predict yields at two contrasting sites. These were based on adjusted rainfall totals over selected time periods linked to growth stages, crop age and degree-days. Yield estimates were reasonable, but the models failed to account for the influence of extreme events such as flooding, and poor pollination due to excess rain during the flowering stage.

In Queensland, researchers are developing a crop forecasting system for the Australian macadamia industry (Stephenson, 2010). It is based on two approaches. First, long-term tree census data are used to forecast yields over a ten-year period. Second, using weather data for the preceding year, the most likely average annual yield in the current year is predicted. Over the first eight years of forecasting, annual estimates were within about 10% of the actual national nut production.

Salinity

According to Batenbender and Hue (1990), there are many areas in Hawai’i with the potential for growing macadamia, but which lack sufficient rainfall. Groundwater in these places is generally brackish due to seawater intrusion. An experiment to determine the response of young macadamia trees (cv. Kau, HAES 344) to salinity under irrigated field conditions was undertaken. The treatments were rainfall only, together with irrigation using freshwater or, to simulate the groundwater conditions, with salt contents of 500 and 1200 ppm (diluted seawater). The trees were irrigated twice weekly to replace water lost by ET (based on a USWB class A pan) during the previous week. There was no leaching fraction. After five years, yields from the three irrigated treatments were similar, as were trunk diameters, and soil and tissue nutrient contents. Trees in the rain-only treatment yielded less than those that were well irrigated.

Although adverse effects of salinity have been noted in the field, there are few data to indicate critical levels (Stephenson and Trochoulias, 1994). The results of the experiments in Hawai'i suggested that macadamia seedlings are moderately sensitive to soil salinity (Hue and McCall, 1989). A reduction in growth rates of 50% occurred at an electrical conductivity of the extract (EC_e) of 5 dS m^{-1}. In New South Wales, Quinlan and Wilk (2005) recommend using irrigation water with a salinity level below 1.2 dS m^{-1}.

Summary: water productivity

1. Macadamia yields are cyclical and highly variable, making it difficult to establish cause and effect.
2. Most irrigation experiments have been poorly planned and/or inconclusive.
3. Yields tend to be reduced more if water stress occurs during the premature nut drop and nut maturation stages of growth than at other times.
4. There are no recommendations based on sound experimental evidence of where irrigation is likely to be worthwhile, or of the yield responses to be expected from water applied.
5. Macadamia is relatively resistant to drought. Drought/high temperatures may influence yields in the following season (yet to be proven).
6. Attempts have been made to develop simple yield forecasting systems.

Irrigation systems

Water management

Runoff is an important component of water management in macadamia orchards. In northern New South Wales, the macadamia industry has expanded rapidly on the north coast and now occupies over 7000 ha of land. Most of the orchards are located on red basaltic (Krasnozem) soil, in high-rainfall (over 1400 mm y^{-1}) areas (Quinlan and Wilk, 2005). Where there is bare soil, water flowing down the macadamia tree trunk (known as stem-flow) has been shown to contribute to soil erosion at the base of the tree, with up to 28% of a rainfall event (by volume) being re-distributed in this way. The average stem-flow over the 16-month monitoring period was 7% (Keen *et al.*, 2010).

Appropriate soil management practices are essential to protect the orchard from erosion. Traditionally, a grass sward is left between rows, and a bare soil strip is maintained along the tree row by regular use of herbicides. This practice makes harvesting easier, but contributes to soil loss and degradation in many orchards (Firth, 2003).

In New South Wales, the creation of so-called 'mounded tree rows' and associated drains that run directly downhill is recommended for runoff control in macadamia orchards (Firth, 2003). It is necessary to ensure that there is groundcover in the inter-rows and drains. As the profile across the inter-row area is not pronounced, cultural operations with machinery are not affected. The other important component of runoff control is the retention of grassed watercourses of sufficient capacity to contain the runoff. Trees should not be planted in or immediately next to these areas. Runoff from the rest of the orchard can then be directed into these watercourses. Full details can be found in Firth (2003).

Irrigation

In both northern New South Wales and southern Queensland, irrigation is considered to be essential, despite the lack of experimental evidence, during the first four years after planting to supplement rainfall, beginning with 40 L tree^{-1} week^{-1} in year 1. However where the annual rainfall exceeds 1300 mm, irrigation of more mature trees normally has no net yield benefit, an increase in nut number being balanced by a reduction in nut size (Quinlan and Wilk, 2005).

In Hawai'i, irrigation of mature macadamia trees is only practised in areas with less than 1250 mm of annual rainfall (Trochoulias, 1988a). For comparison, macadamia orchards in Queensland are generally irrigated in areas where the average annual rainfall is 1140 mm, for example in the Bundaberg region. By contrast in northern New South Wales, where the annual rainfall averages 1600 mm, most of the orchards are rain-fed. Indeed, adverse effects of irrigation have been observed there (Hardner *et al.*, 2004). Nevertheless, yields still fluctuate less in the irrigated areas of Bundaberg than they do in these rain-fed orchards.

The following guidelines for irrigators in Australia have been proposed by Stephenson (1990):

- To aid tree establishment apply 20–30 L tree^{-1} twice a week for the first two months.
- During the remainder of the first year irrigate weekly, unless rain occurs.
- Apply up to 130–150 L tree^{-1} each week in the summer and 30–40 L tree^{-1} in the winter.
- In each successive year, up to year 10, increase the maximum weekly rate by these amounts, so that in year 5 a maximum of 750 L tree^{-1} week^{-1} is applied in mid-summer and by year10, 1500 L tree^{-1} week^{-1}.

These figures were intended to act as a guide only and should be adjusted to meet local conditions, including tree size and spacing, which can vary between 10 × 10 m (100 trees ha^{-1}) and 7 × 4 m (357 trees ha^{-1}). Unfortunately, the planting density to which these guidelines apply was not specified.

Both drip and micro-sprinklers are suitable methods for applying water to macadamia trees. There may be practical benefits from keeping the micro-sprinklers and dripper lines away from the ground, in order to avoid the risks of damage during weed control

Figure 7.7 Irrigating individual macadamia plants with a hosepipe in a recently planted orchard – Malawi (MKVC).

and at harvest. Drip irrigation was first used in mature macadamia orchards in Hawai'i in 1975, and in new plantings in 1979. By 1985, 1800 ha were being irrigated by this method (Young, 1985). The current area irrigated in this way is not known.

Summary: irrigation systems

1. Runoff is an important component of water management in macadamia orchards, and must be controlled.
2. Irrigation is considered to be desirable, despite the lack of experimental evidence, during the first four years after planting (Figure 7.7)
3. Irrigation of mature trees is practised in areas where the average annual rainfall is less than 1300 mm.
4. Guidelines are available for macadamia producers on the quantity of water and the frequency of its application, but these have to be interpreted for local conditions.
5. Both drip and micro-sprinklers are suitable methods for applying water to macadamia trees.

Conclusions

Macadamia is unusual in that it is a crop where the centre of production is very close to its centre of origin in south-east Queensland and north-east New South Wales. It is also in Australia that most of the research on the physiology of macadamia has been undertaken, following earlier work in Hawai'i. The focus for much of this research has been to understand how temperature affects growth and development, particularly the impact of high temperature on the development and retention of the nut. Research has also been directed at how to manage a large self-shading tree so as to make best use of light, and to minimise premature nut shedding. Research is clearly made more difficult by the cyclical and highly variable nature of macadamia yields. It is not easy to establish cause and effect, especially as it takes about 12 months from floral initiation to the completion of nut harvest. Clearly, macadamia has many attributes that make it tolerant of long dry seasons. This also means that mature trees appear to be unresponsive to supplementary irrigation in the areas where it has been evaluated. With a minimum of five years needed to demonstrate a yield response, it is questionable whether the experiments that have been reported have been sufficiently robust to answer the questions posed, namely where and when is irrigation justified, and what is the minimum quantity of water needed. It is difficult to convince sponsors to fund such lengthy research projects of that duration for a specialist (minor) crop, especially when the benefits are uncertain. But this is what is needed for macadamia if the potential of the crop is to be fully exploited.

Summary

The macadamia nut is the only commercial food crop indigenous to Australia. It originated along the fringes of rainforests, only becoming an important internationally traded crop in the late twentieth century. Australia is now the main centre of production, following a lead set by Hawai'i. The crop is also important in Central America and southern Africa. The majority of recent research reported in the literature on the physiology and water relations of macadamia has been undertaken in Australia.

Macadamia is a tall, evergreen tree in which vegetative growth occurs in a series of flushes. Mild water stress suppresses growth, but compensatory growth occurs on re-watering. Flowers form on hardened wood within the leaf canopy. Floral initiation occurs in late autumn, with flowering in the following spring.

Flowering is profuse, but only 5–10% of the flowers set fruit and less than 1% of the flowers reach maturity as fruits, due largely to premature abscission. High temperatures (>30 ºC) can contribute to the shedding of fruit. It takes about 12 months from floral initiation to the completion of harvest. Macadamia root systems are described as relatively shallow and spreading. The tap root can extend to depths >1.2 m, with a dense matt of fibrous roots in the top 0.4 m. Proteoid rootlets are also present.

Stomata are only found on the abaxial surface of the leaf. Macadamia has several attributes that help to explain its apparent tolerance to periodic dry conditions, as found in its native habitat. These include leaves with xeromorphic adaptations, stomatal closure without concurrent changes in leaf water potential and an efficient water transport system. There has only been one serious attempt to measure the actual water use of macadamia. Most irrigation experiments have been poorly planned and/or the outcomes were inconclusive. Nut yields are cyclical and highly variable, making it difficult to establish cause and effect. It is not yet possible to say with evidence where and when irrigation is worthwhile.

Endnotes

1 Kernel = embryo + cotyledons.
2 This compares with 5–10% cited by Stephenson and Trochoulias (1994).

8 Mango

Introduction

The mango tree is believed to have evolved in the subtropical north-east Indo-Burmese region, where it is found growing as a canopy-layer species in the rainforests. Mango has been cultivated for at least 4000 years in India, where it occupies a pre-eminent place amongst fruit crops and is acknowledged as the 'King of the Fruits' (Majumder and Sharma, 1990). The mango fruit can be eaten fresh, frozen, dehydrated, canned or made into jellies, jams, chutneys, pickles and juices. The leaves can be eaten as a vegetable, or used as stock fodder.

Mango trees were introduced into the humid tropics of the Malay Archipelago and South-east Asia 2500–2600 years ago, where the mango became naturalised. It was only in the sixteenth and seventeenth centuries that the mango reached Africa (Figure 8.1), and afterwards Brazil, with the aid of Portuguese traders and travellers. The first introduction into the USA (Florida) was in 1861(Mukherjee and Litz, 2009).

Some mango cultivars evolved in tropical areas and these differ from those that originated in the subtropics. The tropical cultivars, which came from the hot and humid regions of South-east Asia (5–6° N), produce seed with several genetically identical embryos (poly-embryonic Indo-Chinese group). In contrast, those that evolved in the subtropical monsoonal regions of the Indian subcontinent (Assam/Burma border area, 24–26° N), with hot summers, but cooler, dry winters, are mono-embryonic (Indian group) (Mukherjee and Litz, 2009; Schaffer *et al*., 2009; Whiley and Schaffer, 1997). Hybridisation occurs readily between cultivars from both groups. A considerable degree of genetic diversity is probably responsible for the adaptation of mango to a wide range of tropical and subtropical environments. The mango is now grown throughout the tropics (latitude range between 25° N and S) and subtropics (35° N and S), and as far north as latitude 35–37° N in southern Spain (Crane *et al*., 1997). It can be found at altitudes of up to 1400 m in the tropics. The optimum air temperature for mango growth is in the range 24–27 °C. Mango trees have limited cold tolerance and are damaged when temperatures fall below 0 °C. The mono-embryonic cultivars tend to be better adapted to low temperatures than the poly-embryonic ones (Schaffer *et al*., 1994). Although mango is considered to be drought tolerant, and may survive for many months without rain or irrigation, water deficits during the reproductive cycle can adversely affect fruit retention and early fruit growth (Whiley and Schaffer, 1997; Schaffer *et al*., 2009).

Figure 8.1 A symbolic, historic mango tree in a West African village – probably Nigeria (HDT).

India is by far the biggest producer of mango, with 2.31 million ha yielding (in 2010) about 15 million t of fruit annually. China is next with 470 000 ha, producing 4.35 million t. These countries are followed by Thailand (310 000 ha; 2.55 million t), Pakistan (170 000 ha; 1.85 million t) and Mexico (170 000; 1.63 million t). The world totals are 4.95 million ha, producing 37.1 million t (FAO, 2012). Mango is now traded internationally all the year round.

In this chapter, the results of selected water-management-related experiments are summarised, and an attempt is made to draw generic conclusions from an independent perspective. Starting with a description of the stages of development (including roots) of the mango tree in relation to water availability, this chapter reviews plant–water relations, water requirements, water productivity and water management.

Majumder and Sharma (1990) published a general review of mango, whilst Davenport (2007; 2009) described in great detail its reproductive physiology. An overview paper by Léchaudel and Joas (2007) on the influence of pre-harvest factors, including water availability, on post-harvest issues, including fruit quality, is of limited value in the context of this paper. The second edition of a book devoted to the mango (Litz, 1997) has recently been published (Litz, 2009).

Crop development

There are hundreds of mango cultivars in the world, indeed about 1000 cultivars are known to exist in India alone, nearly all of which are of the monoembryonic type. Salient characteristics of the more important of these have been described by Menzel and Simpson (1994b) and by Knight *et al*. (2009). Cultivars referred to in this paper include: Carabao (originally from the Philippines), Chok Anan (Thailand), Haden (Florida), Irwin (Florida), Julie (West Indies), Keith (Florida), Kensington Pride (Australia), Nam Doc Mai (Thailand), Osteen (Florida), Sensation (Florida) and Tommy Atkins (Florida). Rootstocks can be used to limit excess vegetative growth and to impart dwarfing characteristics suitable for intensive, high-density production systems (Reddy *et al*., 2003; Oosthuyse, 2009).

Vegetative growth

The mango is a large, evergreen tree that can reach a height of 30–40 m and live for more than a hundred years. The trees are either grown from seed, or by vegetative propagation with the scion grafted on to seedling rootstocks (Figures 8.2 and 8.3). In south-east Brazil, the recommended plant spacing, under rain-fed, dry conditions, is 10 × 10 m

Figure 8.2 A young mango tree. (HDT).

Figure 8.3 A traditional mango orchard – (HDT).

(100 trees ha^{-1}), with field planting recommended at the start of the rains. By contrast, in the semi-arid north-east of the country, where the crop is irrigated, the tree density is increased to 250 trees ha^{-1} (8 × 5 m) (Pinto *et al.*, 2007). Very high-density planting (e.g. 1600 trees ha^{-1}) is now being encouraged, for example in India (Sharma, 2012).

A terminal meristem produces an indeterminate trunk bearing tiers of branches. Shoots grow in periodic flushes, lasting three to six weeks, during which time the apex produces 10–20 leaves (Davenport, 2009; Davenport and Núñez-Elisea, 1997). A period of ‘dormancy’ then follows. With mango, the time taken for leaves to become net exporters of carbon, rather than net importers, is relatively long (*c*. six weeks) compared with avocado (Whiley and Schaffer, 1997; Schaffer *et al.*, 2009). Vegetative flushes occur one or more times a year on individual stems, the exact number depending upon the age of the tree, the cultivar and the growing conditions.

For example, shoot extension ceases at daily mean air temperatures less than *c*. 15 °C, whilst at 27.5 °C, the number of growth ‘flushes’ over a 20-week period can be between 2.3 (cv. Nam Dok Mai) and 4.7 (cv. Kensington Pride). The critical variable is the duration of the period between flushes, which in this example varied from 36 to 17 to 5 days, respectively (Whiley, 1993).

Flowering

The mango tree produces 300–4000 small (5–10 mm diameter) pink flowers on, predominantly, many-branched, terminal panicles. The panicles are initiated in dormant apical buds on stems that have developed from lateral buds on shoots that flowered the

Figure 8.4 Mango tree in full flower. A mango tree produces 300–4000, small pink flowers on, predominantly, many-branched, terminal panicles. Flowers begin to open early in the morning and anthesis is generally completed by noon – India (HDT).

year before. Both male and hermaphrodite (commonly known as 'perfect') flowers are found on a single inflorescence. Mango flowers begin to open early in the morning and anthesis has generally been completed by noon (Figure 8.4). Mango flowers are cross pollinated, mainly by insects (Iyer and Degani, 1997). Under tropical conditions the period between floral initiation and anthesis can be as little as four weeks. The stimulus that induces flowering in mango trees has been the subject of much debate and study. There are two contrasting situations to consider: (1) the low-latitude tropics and (2) the high-latitude tropics and subtropics, although the two situations obviously overlap, and altitude also needs to be taken into consideration.

Low-latitude tropics

In these areas, the initiation of flower buds generally occurs after at least 6 to 12 weeks of water stress is ended by rain or irrigation. Water deficits prevent vegetative shoots from flushing. The longer this water stress period lasts, the more time there is available for a possible (unidentified) floral stimulus to accumulate (or for the quantity of an inhibitor to diminish). This initiation process has still not been demonstrated consistently. For example, in a glasshouse experiment in Florida (USA; 25° 28′ N 80° 28′ W), Núñez-Elisea and Davenport (1994) were unable to demonstrate that flowering was stimulated by an extended period of water stress. This was thought to be due to the small size of the containers (12 L), which dried out too quickly Subsequently, Lu and Chacko (2000) reported a similar experiment conducted in the open air in Darwin, Australia (12° 25′ S 130° 52′ E), but this time with larger containers (200 L). A controlled water deficit lasting five weeks promoted earlier and more intense flowering in both cultivars, Kensington Pride (72% of the shoots flowered on water-stressed trees, but only 13% on well-watered trees) and Irwin (67% and 4% respectively). The number of fruit (large and medium size) harvested from the water-stressed trees was also greater than those from the well-watered trees. The one exception was cultivar Nam Dok Mai, which appeared not to need an external stimulus, such as low temperature or water stress, to induce flowering (41% of the shoots flowered on well-watered trees).

Research in Colombia suggests that, under tropical conditions, the primary factor controlling flower initiation in mango trees is the age of the last flush (Ramirez and Davenport, 2010). The older the flush the greater the accumulation of a florigenic promoter, which is being synthesised continuously in mango leaves and translocated from the leaves to the buds through the phloem. Water stress, by delaying shoot development (cool conditions during winter in subtropical areas serve a similar purpose), extends the period over which the florigenic promoter is being formed until a critical concentration is reached that induces flower formation (see Ramirez *et al*., 2010a; 2010b and others, for full discussion of the topic).

High latitude tropics and subtropics

In these areas, flower buds are initiated during the cool winter months (night temperatures below 15 °C, day temperatures below 20 °C, for a minimum period of three weeks, cultivar specific). Flowering then occurs in the early spring. Reporting a detailed, controlled-environment experiment in Florida, Núñez-Elisea and Davenport (1995) showed that it was cool temperatures (around 15 °C) during bud dormancy rather than a short photoperiod (11 h) that caused floral induction (for cv. Tommy Atkins). Similarly, warm conditions (near 30 °C) rather than a long photoperiod (13 h) inhibited flowering, and the non-differentiated buds became vegetative. In a similar study in Queensland, Sukhvibul *et al*. (1999) showed how the floral biology of all four cultivars studied (Kensington Pride, Irwin, Nam Dok Mai and Sensation) was affected, in different ways, when inflorescences developed under low temperatures (day/night temperatures at or below 20 °C/10 °C). The potential impact on yield was greatest with cv. Kensington Pride, a poly-embryonic ecotype. As well as these external factors, phytohormones (auxins from leaves and cytokinins from the roots) may also be involved in the initiation and induction of the reproductive cycle in mango (Davenport, 2007, 2009; Davenport and Núñez-Elisea, 1997).

To confound the situation further, it is possible for both low temperatures and water stress to act together to induce flowering in mango. In a field experiment in a reasonably high-latitude tropical site in Queensland, Australia (19 °S), Bally *et al*. (2000) compared the responses of 20-year-old trees (cv. Kensington Pride), in terms of flowering and yield, to deficit irrigation against a well-watered control treatment. The two deficit treatments involved withholding irrigation for specific periods of time, from the first vegetative flush following harvest until either: (1) 90% of the buds were judged to be anatomically floral or (2) 70% of the inflorescences had emerged. In both cases where water was withheld, the number of terminals that flowered was increased (by an average of 20% over three years). In two out of the three years yields were also increased (by an average of 17%). However, since the minimum temperatures during the floral induction period were low enough to induce flowering (10–15 °C), the only valid conclusion is that water deficits had an additive effect on flowering that was initiated by low temperatures prior to the emergence of the inflorescences. It was not possible to explain any of the observed yield responses in terms of the measured parameters.

In Thailand (*c*. 13 °N 100 °E; alt. 5 m), Pongsomboon *et al*. (1997) monitored the changes in, and relationships between, a number of variables associated with flowering in four-year-old mango trees (cv. Nam Dok Mai) during the cool dry season. Although the changes were relatively small, there was a positive correlation ($r = 0.78$) between (pre-dawn) leaf xylem water potential[1] (range –0.3 to –1.0 MPa) and the relative water content (range 98 to 87%). The proportion of terminal shoots that produced flowers increased (from about 40 to 90%) as the xylem water potential ($r = 0.72$) (and also the relative leaf water content, $r = 0.65$) declined. Similarly, there was a positive correlation between the total non-structural carbohydrate content of the terminal shoots and flowering intensity. Although no causal relationship was established, this response was considered to be due to the combined effect of water stress, together with low temperatures suppressing vegetative growth, resulting in carbohydrate accumulation. Flowering intensity was also associated with a decline in giberellic-acid-type substances (GA-3) in the shoot tips.

Out-of-season flowering

Producers are interested in reliable out-of-season flowering in order to provide fruits for market at times of maximum value, especially in the tropics. In the northern hemisphere mango prices are highest in March and April and, as it takes four months from flowering to fruit maturity, flowering induction time needs to be shifted back to October (from February). Successful floral management in the tropics therefore means discouraging the initiation of new shoots, since they are likely to be vegetative, until the resting stems have matured enough to induce flowering shoots to develop (Davenport, 2007; Ramirez *et al*., 2010b). As trees mature, this extended 'rest' period occurs naturally. At high altitudes in the tropics, cool temperatures provide an additional stimulus for flowering in stems of a given age.

According to Davenport (2007), the first step in the initiation of flowering is to synchronise vegetative growth. This is usually achieved through tip-pruning. An adequate supply of water is essential at this time. With localised irrigation, there is still a risk of a second vegetative flush occurring when the rains start, since some roots will have been in dry soil. Reducing nitrogen levels in the leaf discourages a second flush in the rainy season.

Fruiting

The mango fruit is a large fleshy drupe containing edible mesocarp (Figure 8.5). It is very variable in terms of size and shape, and the colour at maturity is cultivar-dependent. The fruit is rich in vitamins A and C. Many fruitlets form on each panicle, but more than 80% are shed (fruit drop) during the first four weeks after fruit set. Water stress should be kept to a minimum during the first four to six weeks after anthesis. This

Figure 8.5 Mango tree with fruit. The mango fruit is a large fleshy drupe containing edible mesocarp. It is very variable in terms of size and shape, and the colour at maturity is cultivar-dependent – Sierra Leone (RCC). See also colour plates section.

is when cell division is occurring and the cell walls are being synthesised (Schaffer *et al.*, 1994). Between 8 and 13% of the flowers set fruit, but less than 1% of these fruit reach maturity (Davenport and Núñez-Elisea, 1997; Davenport, 2009). Some cultivars produce only one mature fruit on each panicle. Fruits take from three to four months to mature. By year 10, individual trees can produce 400–600 fruits annually, and by year 40, 2500 fruits, depending on tree spacing (Menzel and Simpson, 1994b). Mango is normally harvested green, and the fruit then ripens during the postharvest period.

Roots

The primary purpose of a pioneering investigation in Pusa, India was to investigate the extent to which grass adversely affects the growth, including roots, of a range of fruit tree crops (Howard, 1925). Root systems of trees established in the field during 1914 were exposed at intervals over a three-year period (1921–1923), and the extent and periodicity of root growth recorded in great detail. The results were expressed in a series of line drawings.The monsoon lasted from mid-June to mid-October. The water table was at a depth of about 6 m for six months, but it rose rapidly after the rains began and came within ‘a few feet’ of the surface in August and September, before falling again after the monsoon ended. Flowering in mango trees occurred in February/early March, after which new vegetative shoots were produced. The mango fruit was ripe at the start of the rains.

To give examples of the detailed observational skills exhibited by Howard (1925), the following quotes about mango are taken from the text:

> *The large superficial roots give off smaller branches to the deep soil layers (followed in 1921 to 4.7 m depth)… the gradual downward movement of root activity after the rains has been observed on several occasions. On October 22 1921, absorbing roots were not found below 1.12 m… the next year an exposure was made a month later… root activity had proceeded as far as 1.37 m from the surface, but below this point the roots were dormant. At the end of January, when the flower buds were beginning to swell, root activity had reached 2.36 m. By March 10 1923, at the beginning of the hot season (during the flowering period), the lower roots were active down to 4.7 m.*

It was also observed by Howard (1925) that:

> *The root hairs of the mango were short, stiff and dark, reddish brown in colour, and did not readily decay; on June 9 1922 new roots were abundant, the longest being 1 cm (six days after the rains began); August 14–22, 1921, many aerotropic active roots in the upper 0.30 m of soil, new roots growing horizontally at 0.51 m, going downwards at 0.66 m and 0.76 m; October 22–24, 1921, after the fall of the ground water, below 1.12 m and down to 3.96 m the root system was dormant; many active roots in upper 0.25 m; at 0.25 m many new roots growing towards the surface; January 27–February 2 1923, flower buds swelling, exposure made to 2.8 m, new roots found at various depths down to 1.8 m, the root system was dormant below this depth.*

In Florida (USA), Willis and Marler (1993) adopted a different approach. By tracing each root growing against the glass wall of an observation chamber, they recorded root growth of two cultivars (Keitt and Julie), both grafted on to Turpentine rootstock, over a period of 12 months. Roots grew fairly continuously, with only brief periods when there was little or no root extension. Both cultivars behaved in similar ways. By contrast, shoot growth was cyclic with distinct periods of shoot extension (during the year cv. Keitt had four vegetative flushes and cv. Julie five), followed by periods of inactivity. There were no consistent relationships between root and shoot extension rates.

In an investigation of feeder root distribution in Bangalore, India, Bojappa and Singh (1975) found that the greatest concentration of roots occurred within 0.60 m radius of the trunk and within 0.15 m of the soil surface in both young and mature mango trees. For young trees, 90% of the roots were within a radius of 1.8 m from the trunk, and for older trees within 3.6 m. There is little doubt that the roots of the mango tree can reach considerable depths. For example, Singh (1977) reported that roots of mango had been recorded at depths of 5.5 m and, in the case of a 60-year-old tree in Bihar (India), 4 m.

Summary: crop development

1. The mango is a large, long-lived, indeterminate evergreen tree that can reach a height of 30–40 m.
2. Cultivars that evolved in hot, humid conditions (Indo-Chinese group) differ from those that originated in subtropical regions (Indian group).
3. The mango is adapted to a wide range of tropical and subtropical environments.
4. The shoots grow in periodic flushes, lasting three to six weeks, during which 10–20 leaves are produced.
5. The base temperature for shoot growth is about 15 °C.
6. Flowers form on panicles that are initiated in dormant apical buds, which develop from lateral buds on shoots that have flowered the year before.
7. In the low-latitude tropics, flower buds are initiated after a period of water stress (6 to 12 weeks duration) is ended by rain or irrigation (the age of the shoot also plays an important role).
8. In the high-latitude tropics and subtropics, flower buds are initiated during the cool winter months (night temperature below 15 °C and day temperature below 20 °C for a minimum of three weeks, cultivar-dependent).

Figure 8.6 Mango tree with fruit. Many fruitlets form on each panicle, but more than 80% are shed (fruit drop) during the first four weeks after fruit set – Sierra Leone (RCC). See also colour plates section.

9. In contrast, warm conditions (30 °C) results in undifferentiated buds becoming vegetative.
10. Only about 10% of the flowers set fruit and then more than 90% of the fruitlets that form are shed during the following four weeks. After flowering, it takes the fruit three to four months to mature (Figure 8.6).
11. Roots extend in depth to at least 5 m. Roots are particularly active in the top 0.25 m. There are no consistent relationships between shoot growth and root growth: roots grow more or less continuously.

Plant–water relations

In a review paper, Whiley (1993) wrote the following: 'Despite the importance of this fruit crop, there is little published data on the basic physiology of the (mango) tree in respect of gas exchange and water relations and their interactive response with the environment.' He then went on to describe the research that was underway at the time. Some progress has been made since then. This is now described under the following headings: Stomata and Gas exchange.

Stomata

According to Purseglove (1968), stomata are present on both leaf surfaces, but with a greater number on the lower (abaxial) surface. By contrast, Wahdan *et al.* (2011), in a comparison of two new genotypes (both mono-embryonic) in Egypt, counted the stomata on the lower surface only (it is not stated whether they looked on the upper surface). For one cultivar, the average density was 384 stomata mm^{-2}, and for the other 678 stomata mm^{-2}. Similarly, Urban and Jannoyer (2004), citing Ali *et al.* (1999), reported stomata densities of 700 mm^{-2} on the lower surface of fully expanded mango leaves, but 1900 mm^{-2} on partially expanded young leaves. There is clearly a range of values.

In Australia, Lu (2006) found the stomata opened rapidly from about 0700 h with conductance reaching a maximum at about 0900 h. This was then followed by a steady but slow decline in stomatal opening until about 1800 h, after which the stomata closed rapidly.

In an unusual laboratory experiment on the island of La Réunion, Urban and Jannoyer (2004) monitored the transpiration rate from excised mango leaves of three cultivars (Haden, Heidi and Lirfa) at three leaf development stages. A reduction of only 2% in the leaf water content resulted in complete stomatal closure. This was taken as an indication of the capacity of the mango to protect itself against excessive water loss.

In northern Australia, Goodfellow *et al.* (1997) studied the impact of carbon dioxide enrichment of the air (700 µmol mol^{-1}) on stomatal conductance and assimilation by mango saplings (cv. Kensington Pride) over a 28-month period. Reduced stomatal conductance in response to the elevated CO_2 was attributed to a reduction in both the stomatal density (by about 17%) and stomatal aperture. At both normal and enhanced CO_2 levels, stomatal conductances declined curvilinearly with increasing leaf-to-air saturation deficits (range 1.5 to 5.0 kPa). In contrast, light-saturating assimilation declined linearly. Total plant biomass was substantially increased in the elevated CO_2 treatment throughout the experiment.

Gas exchange

In a paper reporting the results of measurements made 20 years earlier, Lu *et al*. (2012) compared the responses of five mango cultivars in the seasonally wet–dry tropics of northern Australia, in terms of photosynthesis and stomatal conductance. The five cultivars belonged to the two distinct groups, poly-embryonic (cvs. Kensington Pride and Strawberry) and mono-embryonic (cvs. Haden, Irwin and Tommy Atkins). Measurements were made at two contrasting sites: one near Darwin (12° S 130° E; alt. 13 m) could be described as humid–hot, with a short dry season and the other, which was located at Katherine (14° S 132° E; alt. 108 m), was more semi-arid with distinct wet and dry seasons. Maximum values occurred during the wet season, but it was during the dry season that the largest differences between the cultivars were observed. Net photosynthesis was then greater in the three mono-embryonic cultivars than in the two poly-embryonic cultivars. Both photosynthesis rates and stomatal conductances were negatively correlated (linear) with the saturation deficit of the air (range 1.5 to 4.0 kPa) with all five cultivars. The two poly-embryonic cultivars were particularly sensitive to dry air, especially cv. Kensington Pride (of Australian origin). A similar negative relationship between stomatal conductance and saturation deficit had previously been reported by Whiley and Schafer (1997), but over a narrow range of saturation deficit (0.5 to 1.5 kPa).

The shapes of the diurnal curves (for conductance and photosynthesis) were similar in both the wet and dry seasons, but, for conductance, were at a lower level in the dry season, even when irrigated. In contrast, transpiration rates in the wet season increased during the morning, before peaking in mid-afternoon and then declining rapidly. In the dry season, photosynthesis rates, conductance and transpiration rates were less for cultivar Kensington Pride than for those recorded for other cultivars throughout the day. In the case of sap flow measurements (Granier's heat dissipation method), it was necessary to make an allowance for spatial variation in the sap flux density within the sap wood (Lu *et al*., 2012) (see below).

The fruit-setting and fruit-development period was the time of maximum environmental stress, with gas exchange remaining low despite a wet (irrigated) soil. Net photosynthesis and stomatal conductance were both positively correlated on a diurnal and a seasonal basis, and during the wet and dry seasons. Because of excessive latex exudation, leaf water potential measurements (with a pressure chamber) were not considered to be a reliable indicator of tree water status (Lu, 2006).

Urban *et al*. (2008) working in La Réunion (20° 52′ S 55° 31′ E), investigated why net photosynthesis rates of leaves of mango situated close to an inflorescence were lower than those of leaves on vegetative shoots. Measurements were made on recently matured leaves on vegetative terminals and on floral terminals of four-year-old trees growing in large lysimeters. These showed that net photosynthesis was lower on leaves close to a developing inflorescence as a result of reduced stomatal and mesophyll conductances. The photosynthetic capacity of the leaf was also reduced. The authors inferred that this reduction in the photosynthetic capacity, and also in the nitrogen content (per unit leaf area), was the result of sink limitation. This suggested that perhaps nitrogen was reallocated at the expense of the photosynthetic process. Parameters measured on leaves close to panicles bearing set fruits were intermediate in value to those on vegetative shoots and on leaves close to an inflorescence, suggesting that the changes in net photosynthesis associated with flowering are reversible.

Mango trees can maintain a high water status when under water stress through osmotic adjustment, which is attributed to the presence of latex (Schaffer *et al*., 1994). Similarly, Whiley (1993) concluded, after citing others, including Pongsomboon *et al*., 1992) that the reason why mango is relatively drought tolerant was because it maintained turgor in its leaves when subjected to a water deficit. Zero turgor occurred at a leaf water potential of –1.75 MPa, whilst permanent leaf damage only occurred when the relative water content declined to 77%, which is much higher than the values reported for other tree crops (e.g. macadamia).

Summary: plant–water relations

1. Stomata occur on the lower (abaxial) surface of mature leaves at densities of 400–700 mm^{-2}.
2. When well watered, the stomata open rapidly in the morning. Maximum conductance in the low-latitude tropics is reached at about 0900 h, followed by a slow but steady decline until 1800 h when the stomata close.
3. A reduction in the leaf water content of only 2% results in complete stomatal closure.
4. Raising the CO_2 concentration of the ambient air (to 700 μmol mol^{-1}) reduced the stomatal conductance (due to fewer, smaller stomata), but total biomass production was increased.
5. Rates of photosynthesis and stomatal conductance are correlated and both are negatively correlated with the saturation deficit of the air (range 0.5 to 4.0 kPa).
6. There is some evidence that cultivars differ in the sensitivity of the responses of the stomata to dry air.
7. During the dry season, net photosynthesis rates by cultivars from the Indian group exceeded those by cultivars from the Indo-Chinese group.
8. Net photosynthesis rates of leaves close to an inflorescence are less than those of leaves on vegetative shoots.

Crop water requirements

Several different methods have been used to determine the water use of mango trees, with mixed success. These include the sap-flow, Bowen ratio, eddy-correlation and soil water-balance techniques. Unfortunately, in several cases, there is a lack of clarity in the way that the results have been reported. Research on crop water requirements has been conducted in three countries: Australia, Brazil and South Africa.

Australia

Lu and Chacko (1997) successfully evaluated the suitability of Granier's sap-flow system for measuring transpiration by 10-year-old mango trees (cv. Kensington Pride) in the seasonally wet–dry tropics in northern Australia (12° 25′ S 130° 52′ E). During the dry season, water use averaged 100 kg tree^{-1} d^{-1} when irrigated, and 60 kg tree^{-1} d^{-1} without irrigation. During the rains the corresponding value was 126 kg tree^{-1} d^{-1}. They compared these results with those obtained gravimetrically, and with the 'cut tree' method. The results from Granier's sap-flow method were believed to be within 6% of the 'true value'.

This evaluation found evidence of circumferential variation in sap-flow rates (different readings between the east and west sides of the tree) and also radial variability. This was largely due to three characteristics of a mature mango tree:

- There is no visibly distinct heartwood (even when the tree is 20–30 years old).
- Patterns of sap flow may be influenced by orchard management practices such as grafting, pruning and localised irrigation.
- Training a mango tree to have a very short trunk means that there may be branch scars or branches close to where the sensors are sited.

Lu *et al.* (2000) subsequently addressed these complications. They found that, under changing soil water conditions, correlations between different aspects (i.e. the radial position of the sensor probes on the trunk relative to the compass) and between the depths of insertion of the sensors were not constant. This meant that a large number of sensor probes were necessary to get a realistic estimate of total sap flow. However, over a period when soil water was freely available, the depth profiles remained relatively constant. As a result, a method for calculating total sap flow in a mango tree from sap flux density measurements made 0–20 mm below the cambium was developed and successfully evaluated.

Brazil

The mango is widely grown in Brazil, particularly in the semi-arid north-east region, where the mean annual rainfall is about 400 mm. Using the Bowen ratio energy-balance method, as well as the water-balance approach, Silva *et al.* (2007) monitored evapotranspiration from a mango orchard over two successive seasons, June to November 1998 and 1999, in this region at Petrolina (09° 09′ S 40° 22′ W; alt. 366 m). The trees were spaced 8 × 5 m (250 trees ha^{-1}). They were 5.2 m tall with a leaf area index of 13–15 (very large). Irrigation (drip) was applied daily to keep the soil profile close to field capacity. The total rainfall over each dry season was only about 50 mm, whilst 950 and 1145 mm of irrigation water was applied during 1998 and 1999 respectively. The proportion of the net radiation dissipated as latent heat was greater at times of low evaporative demand than when evaporation rates were high, exceeding 70% in both years. Over the season, actual evapotranspiration rates (*ET*) averaged 4.5±0.4 mm d^{-1} in 1998 and 4.3±0.6 mm d^{-1} in 1999. The corresponding reference crop values (ET_o, Penman–Monteith) were 5.3±1.03 mm d^{-1} and 4.9±1.01 mm d^{-1}, respectively. Assuming that, for a well-watered crop, *ET* was equal to ET_c (potential evapotranspiration), the values of the crop coefficient (K_c) were 0.85 in 1998 and 0.88 in 1999. The peak *ET* rates in each year were 5.2 and 5.5 mm d^{-1} respectively.

Azevedo *et al.* (2003) had previously published a very similar account of the same experiment, but with more details of the methodologies used four years earlier, and only reporting the results for 1999. One surprising outcome was the very close agreement in the estimates of *ET* between the two methods used (Bowen ratio and water balance). For example, in 1999, the cumulative totals over the period of measurement were 552 mm (Bowen ratio) and 555 mm (water balance), both with a mean water use of 4.1 mm d^{-1} (Azevedo *et al.*, 2003). Considering the differences in the two methodologies this agreement had to be fortuitous, resulting, perhaps, from a cancellation of errors. There was further confusion in that the cumulative *ET* totals reported in the subsequent paper (Silva *et al.*, 2007) were (presumably) the averages for both methods (it was not made clear), namely 676 mm in 1998 (4.6 mm d^{-1}) and 719 mm in 1999 (4.8 mm d^{-1}). These figures are different from the ones reported by Azevedo *et al.* (2003) and summarised above. No clear explanation was offered for these discrepancies. Perhaps, the most that can be taken from these two papers is that potential rates of evapotranspiration (ET_c) from mature mango trees in this region of Brazil, between flowering and fruit maturation, are between 4 and 5 mm d^{-1}. Subsequently, Teixeira and Bastiaanssen (2012) evaluated several methods for determining and interpreting field measurements of energy fluxes over a micro-sprinkler-irrigated mango tree orchard, including the eddy-correlation and Bowen ratio techniques. Depending on the method used, growing-season *ET* totals (or are they annual totals?; it's not made clear) varied between 965 mm and 1552 mm (2003/04), and between 1127 mm and 1440 mm (2004/05).

Teixeira *et al.* (2008) researched this topic further by using the eddy covariance technique to measure actual evapotranspiration (*ET*) in a mango orchard in the semi-arid region of the Sao Francisco River basin in north-east Brazil (9° 22′ S 40° 34′ W). Measurements were made from 2003 to 2005; the cultivar was Tommy Atkins, 12-years-old in 2003, the trees were spaced 10 × 10 m; the tree height was 5.5 m; the leaf area index was 5.6; the soil was sandy (red-yellow Latossoil); the water table was at a depth of 2.5 m; the effective root zone was about 1.2 m deep and the orchard was irrigated with micro-sprinklers. The authors plotted the outputs from the eddy covariance method (turbulent energy flux $= H + \lambda E$) against the energy balance (available energy $= R_n - G$). The slope of the line gave the energy balance ratio (0.88). The latent heat flux (λE) was always greater than the sensible heat flux (*H*) during daylight hours, which in turn exceeded the soil heat flux (*G*). The net radiation term (R_n) is the amount of energy available at the crop surface (incoming solar radiation less reflected short-wave radiation and less re-emitted long-wave radiation) that can be used to heat the air (*H*), evaporate water (λE) or heat the soil (*G*). A very small proportion of solar radiation is utilised in photosynthesis.

The aim of these field measurements was to quantify how much of the net radiation contributed to the evaporation process. In this experiment, 89% of Rn was used to evaporate water (transpiration and evaporation) in the first year and 80% in the second year. When converted to the equivalent depths of water, these represented annual *ET* totals of 1492 mm in 2003/04 and 1346 mm in 2004/05, a combined average daily *ET* rate of 3.7 mm d^{-1}, with peaks of 6.3 mm d^{-1} and 5.1 m d^{-1} in the two years, values close to those cited above. Minimum *ET* values were 0.6 mm d^{-1}. When averaged over 20-day periods, the crop coefficient ($K_c = ET_c/ET_o$), where ET_o is the reference crop evapotranspiration (Penman–Monteith equation; weather data obtained from an automatic weather station), varied between 0.65 and 1.05. The high values occurred during periods when the soil surface was frequently wetted by rain or irrigation (micro-sprinklers were used to irrigate the trees, not drip). When evapotranspiration was partitioned between transpiration and evaporation the mean values of each in year 1 were 3.06 mm d^{-1} and 0.75 mm d^{-1} and, in year 2, 2.79 mm d^{-1} and 0.85 mm d^{-1}, respectively.

Using λE (evaporation) flux profile relationships, Teixeira *et al.* (2008) calculated the seasonal changes in the aerodynamic (r_a) and crop canopy (r_c) resistances. Relatively high r_c values were associated with dry air conditions, whilst high r_a values occurred during the rains when r_c was low. The 24-hour annual mean r_c and r_a values were 135 s m^{-1} and *c*. 37 s m^{-1}, respectively. The orchard could be described as aerodynamically ‘rough’.

Silva *et al.* (2009) reported the results of a deficit irrigation experiment in north-eastern Brazil (Petrolina) that was designed to identify the irrigation regime that gave the highest water productivity. The soil was sandy (90% sand), classified as a red-yellow Latosol, with an available water content of only about 8%. The water table was 4–6 m below the surface. The 12-year-old trees (cv. Tommy Atkins) were spaced at 10 × 5 m (200 trees ha^{-1}), and irrigated by sprinklers, with one sprinkler per tree. There were four levels of water application: 0.70, 0.80, 0.90 and 1.00 × ET_o, the reference crop evapotranspiration (Penman–Monteith). The experiment lasted two years, 2005 and 2006. Actual water use (*ET*) was estimated using the soil water-balance approach. This included estimates of drainage from and/or capillary rise into the root zone (based on a profile of tensiometer readings from 0.2 to 1.2 m depth). The average total irrigation amounts applied in a season were between 365 mm and 550 mm. In addition there was 154 mm of rain.

Cumulative evapotranspiration totals (*ET*) averaged over both seasons (from flowering to fruit maturity) were between 370 mm (0.70 × ET_o) and 480 mm (1.00 × ET_o, the control treatment). Daily ET_c rates in the well-watered control treatment were between 3.6 and 5.6 mm d^{-1}. Yields of fresh fruit were similar, ranging between 28.0 t ha^{-1} (the control) and 31 t ha^{-1} (0.90 × ET_o). The authors plotted a not-very-convincing quadratic curve through the four data points. Water productivities based on irrigation water applied were between 5.1 kg fruit m^{-3} (control) and 8.0 kg m^{-3} (0.70 × ET_o). The corresponding values for actual evapotranspiration (*ET*) were 5.8 and 7.9 kg m^{-3}. These values are considered again below in the context of other work on water productivity.

South Africa

Over a six-year period, Mostert and Hoffman (1997) monitored the water use of 12-year-old (initially) mango trees (cv. Fascell; tree density = 210 ha^{-1}) in the Eastern Lowveld in South Africa (25° 33′ S 30° 58′ E; alt. 1000 m). Tensiometers were installed at depths of 300, 600 and 900 mm. The amount of water needed to bring the soil profile (to a depth of 900 mm) back to field capacity when the average readings at all three depths had reached either –30 kPa or –60 kPa was monitored with flow meters. It was assumed that only 70% of the orchard area was watered. Similarly, it was also assumed that 70% of the rainfall was effective. The total annual potential water use (ET_c) averaged over the six years for the frequently irrigated treatment was 1200 mm (range 1050 to 1390 mm). These figures include 0.70 × the annual rainfall, which averaged 494 mm (range 293 to 639 mm). It's not clear whether these were net or gross figures. The ET_c totals needed to be adjusted in order to give values representative of the total ground area (i.e. divided by 0.7). Unfortunately, this was all rather poorly explained in the text. Peak rates of water use reached about 4.4 mm d^{-1} in October/November, falling to about 2.1 mm d^{-1} in June (these are assumed to be net values; the equivalent gross values would be 6.3 and 3.0 mm d^{-1}, respectively).

Yields of fruit were recorded in this experiment, but with large coefficients of variability (average 24%). The yield differences were only significant in two years, when the frequently irrigated treatment out-yielded the rain-fed treatment by 51% (158 kg tree^{-1} cf. 104 kg tree^{-1}). Similarly, in one year only, the two treatments that were not irrigated in the winter months (May to August, the time of flower bud development), but were afterwards irrigated frequently out-yielded the control rain-only treatments. They also out-yielded (marginally) those that were not stressed in the winter months. Over the six years, the average yields from trees that were stressed in the winter months was 30.5 t ha^{-1}, compared with 27.8 t ha^{-1} from those trees that were watered at that time. This yield advantage in favour of a water-deficit treatment was thought to be the result of a vigorous flush of flowers following the relief of water stress. Caution is recommended when interrogating the data reported in this paper (Mostert and Hoffman, 1997). After making several assumptions, the water productivity for the incremental irrigation application was estimated to be only about 1.0 kg m^{-3}

Summary: crop water requirements

1. A range of techniques has been used to measure/estimate water use by mango trees, with some success: unfortunately the results of this research have not always been well reported.
2. After allowing for complications associated with the properties of the trunk, the sap-flow method is believed to be capable of monitoring transpiration by a mango tree.
3. There was surprisingly good agreement between the seasonal ET totals derived from the Bowen ratio method and the soil water-balance method.
4. The best estimates of water use by mango trees in tropical humid areas suggest mean seasonal ET_c rates of 4–5 mm d^{-1}, with peak rates of 5–6 mm d^{-1}.

5. The value of the crop coefficient (K_c) varies between 0.65 and 1.05, depending on the frequency and extent of wetting (linked to the method of irrigation) of the soil surface, and the tree density.

Water productivity

This section considers the evidence from field experiments of the yield response to irrigation water by mango. This is quantified in terms of the mass of fresh fruit (kg) for each unit of water applied (m^3). It can also be expressed on a unit of evapotranspiration and/or transpiration basis. Local custom also has its own units for measuring the same thing. For example, in Australia, water productivity, as it is also known, is recorded commercially as the weight (t) of packed class 1 fruit per ha per ML (Bithell, 2012). Water productivity is not an easy parameter to measure, especially with a long-term tree crop prone to biennial bearing. Research on this topic has been undertaken in Brazil, Thailand and Spain.

Brazil

The recommended fertiliser levels (N:P:K) in Brazil for the mango crop vary according to the expected productivity (from <10 to >50 t fruit ha^{-1}), the nutrient content of the leaf, the element itself, and whether or not the trees are irrigated (Pinto *et al.*, 2007). The timing and proportions of the total annual application also vary with whether or not the crop is irrigated. Maximum recommended nutrient inputs for a rain-fed crop are 50 kg N ha^{-1}, 34 kg P ha^{-1}, and 66 kg K ha^{1}. For an irrigated crop these figures are increased to 120 kg N, 64 kg P and 208 kg K ha^{-1}. 'Fertigation' is encouraged with drip or micro-sprinklers, In Brazil, yields of up to 40 t ha^{-1} are possible with irrigation, but average yields under rain-fed conditions are in the range 8–12 t ha^{-1}.

The recorded yields of fresh fruit from the commercial mango orchard in north-east Brazil, where Teixeira *et al.* (2008) measured actual evapotranspiration and its components (summarised above), were 41.5 t ha^{-1} in 2003/04 and 48.4 t ha^{-1} in 2004/05. The corresponding values for water productivity for each of the two years were: 4.8 and 4.3 kg m^{-3}, when based on the volume of irrigation water applied, 2.8 and 3.6 kg m^{-3}, when based on evapotranspiration and 3.6 and 5.4 kg m^{-3}, when based on transpiration, respectively.

Thailand

The most important mango-producing country in South-east Asia is Thailand. Apart from being a common house garden tree, mango is produced on medium to large plantations all over the country. The majority of fruit is grown for local consumption. One cultivar is particularly popular (Chok Anan). It is unusual in that in addition to the main harvest in May there are also two additional out-of-season harvests in June and August, as a result of off-season flowering. This has certain advantages to the farmer, but it does lead to biennial bearing. Most of the on-season fruit development occurs in the dry season when farmers need to apply supplementary irrigation to ensure high yields of good quality, but there is competition for water from other users (Spreer *et al.*, 2009a).

This therefore was the context in which Spreer *et al.* (2007; 2009a) compared the responses of mango (cv. Chok Anan grafted on to Talap Nak rootstock, to four irrigation treatments: well-irrigated (100% ET_c), rain-fed only (no irrigation), regulated deficit irrigation (50% replacement of ET_c) sustained over the dry season (when rainfall ranged from 70 to 333 mm), and partial root-zone drying (50% replacement of ET_c, water applied to alternate sides of the tree at two-week intervals). The experiment was located in an orchard near Chiang Mai (18.53° N 100.03° E; alt. 350 m). The trees were 10 years old at the beginning of the experiment. The soil was classified as a Regosol, characterised by a high stone content and a low water-holding capacity. The experiment continued for four years (2004–2007). Unusually, the authors used 0.75 and 0.90 as the levels of confidence needed to determine statistically significant differences in fruit yields as well as 0.95 (the usual minimum level). The yield response curves (production functions) were also misleading. Quadratic curves were plotted for each of the four years with only four data points. These relationships were then used to identify a (false) optimum water input (irrigation plus rain). From a visual assessment, it would have been equally justified to draw a two-stage linear response curve, or even a single straight line.

Over the four years (which included two ‘on’ or good-yielding years and two ‘off’ years; between 38% and 75% of the trees were alternate bearing) the average annual yields were similar for all three irrigated treatments, at about 81 kg tree^{-1}. The rain-fed trees averaged 19% less at 66 kg tree^{-1} (the tree density was not specified) As a result, the water productivity was considerably higher in the two deficit treatments than it was for the well-watered trees. In a separate paper, Spreer *et al.* (2009b) reported the results for the first two years, 2004 and 2005, of what appears to be the same experiment. It is not easy to reconcile the results as presented in the three papers by Spreer *et al.*

Spain

The provinces of Granada and Malaga in south-east Spain represent the northern limit of the commercial production of mango. This is a subtropical, Mediterranean climate characterised by dry, hot summers and wet autumns and winters. The average annual rainfall is about 450 mm. Zuazo *et al.* (2011b) reported the results of a field irrigation experiment conducted near Granada (36° 48′ N 3° 38′ W; alt. 195 m) over three seasons (2006–2008). With the aim of identifying the most productive irrigation schedule, the treatments were based on four different levels of replacement of water lost by evapotranspiration (ET_c). These were: 100% ET_c (the control); 75% ET_c; 50% ET_c and 25% ET_c, where ET_c is the evapotranspiration from a well-watered mango crop. When less than the maximum amount of water is applied, this is known as ‘sustained deficit irrigation’. Unfortunately, there was not a rainfall-only (unirrigated) control treatment. ET_c was calculated from the Penman–Monteith estimate of reference crop evapotranspiration (ET_o), with crop coefficients (K_c) derived from drainage lysimeter data. These were adjusted for tree size ($K_c = 0.51$ at flowering, 0.72 at fruit set and 0.60 during fruit expansion) ($ET_c = K_c\ ET_o$). The 12-year-old trees (their age at the start) were grown on bench terraces (cultivar Osteen; density 600 trees ha^{-1}) and the soil texture was 68% sand, 24% silt and 8% clay.

The average depths of water applied with drip irrigation to each treatment over the three seasons were 474 mm (control), 342 mm, 258 mm and 168 mm, respectively. The frequency of irrigation was not reported. The corresponding fruit yields were 24.1, 22.5, 30.7 and 16.0 kg tree^{-1}. Only yields from the lowest-yielding treatment (25% ET_c) were significantly different ($P \leq 0.05$) from the other three. This may have been a chance result. In the same order, water productivities averaged 3.1, 3.9, 7.1 and 5.7 kg m^{-3}, (overall mean 5.0 kg m^{-3}) with the 50% ET_c treatment apparently more than twice as productive as the well-irrigated 100% ET_c treatment. Using a derived binomial function ($y = -3.42\ x^2 + 32.34x - 47.13$; $R^2 = 0.85$, $n = 12$, where y is the yield of fresh fruit (kg tree^{-1}) and x is the volume of irrigation water applied (m^3 tree^{-1}), the authors identified the optimum seasonal water application (for fresh fruit yield) as being between 4.5 and 5.5 m^3 tree^{-1} (270–330 mm). Yields were positively correlated with the number of fruits per tree.

Summary: water productivity

1. Experiments intended to quantify the yield response to water by mango trees have produced results of limited value due in part to poor design and/or because they were badly reported.
2. The long-term nature of the crop and the tendency for biennial bearing are added complications.
3. The range of tree densities (from 100 to >3000 trees ha^{-1}) now used commercially adds another dimension of complexity to the challenge of determining water productivity.
4. The range of water productivities reported for fully irrigated crops extended from 3 to 5 kg (fresh fruit) m^{-3} (irrigation). The overall mean value was 4.3 kg m^{-3}.
5. For deficit-irrigated crops the spread was from 3 to 6 kg m^{-3}. The overall mean was slightly higher than it was for well-watered crops (5.6 kg m^{-3}; excluding the results from Thailand) (Table 8.1).
6. This difference in water productivity provides (very) limited evidence that deficit irrigation of mango may be worthwhile.
7. Only one experiment allowed yield responses to evapotranspiration and to transpiration to be determined.

Water management

A number of different topics are included under this heading. These include irrigation methods, irrigation scheduling, salinity and intensification. Only research that is specific to mango is described here.

Table 8.1 Water productivity (kg m^{-3}) for mango based on irrigation water applied (I) evapotranspiration (ET) and transpiration (T). Please see text for further details of each experiment.

Country	Treatment/year	Water productivity			Reference
		I	ET	T	
NE Brazil	Full irrigation 2003/04	4.8	2.8	3.6	Teixeira *et al.* (2008)
	2004/05	4.3	3.6		
	Full irrigation 1998/99	5.1	8.0		da Silva *et al.* (2009)
	Deficit irrigation 0.7 × ET_o 1998/99	5.8	7.9		
SE Spain	Full irrigation 2007/08	3.1			Zuazo *et al.* (2011a)
	Deficit irrigation 0.75 × ET_c 2007/08	3.9			
	Deficit irrigation 0.5 × ET_c 2007/08	7.1			
	Deficit irrigation 0.25 × ET_c 2007/08	5.7			
N Thailand	Range of values:				Spreer *et al.*(2009a)
	2005	8–14			
	2006	4–14			
	2007	9–17			

Irrigation methods

Any method of irrigation can be adapted for use in a mango orchard, but the tree density will strongly influence the final choice. In a modern orchard, drip and micro-sprinkers are likely to be the preferred options (Figures 8.7 and 8.8). In the deficit-irrigation experiment reported above, Spreer *et al.* (2009a) divided some of the plots into two halves, one of which was irrigated with drippers and the other half with micro-sprinklers. Yields of fruit and water productivities resulting from the two irrigation methods were similar. Lu (2006) reported that drip irrigation was not commonly used in mango orchards, farmers in Australia preferring under-tree micro-sprinklers.

Irrigation scheduling

In order to induce flowering, irrigation is usually withheld from mango trees from the end of the wet season in the low-altitude tropics (April in the southern hemisphere) until flowering. Irrigation then recommences when 75% of the canopy is in flower (Lu *et al.*, 2000).

In Australia, Lu (2006) compared three irrigation scheduling methods in a field trial with mango trees:

(1) a control treatment, which was irrigated according to local authority recommendations;

Figure 8.7 Drip-irrigated mango tree (cv. Kent, 17 years old) – Petrolina-PE, Brazil (LM).

(2) irrigation determined by measurements made with a micro-dendrometer, which monitors changes in twig diameter;
(3) soil water monitoring (with a capacitance probe). Actual water use was recorded by recording xylem sap flow.

A ‘shrinkage index’ based on the micro-dendrometer readings was found to be an excellent indicator of the onset of water stress. This was because a much higher proportion of the water applied to a tree was actually transpired (as opposed to evaporated) when the micro-dendrometer was acting as the indicator (shrinkage index = 77%) of when to irrigate. This compared with values of 31% and 38% for the other two scheduling methods, respectively. Monitoring sap flow was found to be a less sensitive indicator of when to irrigate (Lu, 2006).

Lu (2006) recognised that both the dendrometer method and sap-flow measurements were far from being practical for growers to use for scheduling irrigation. Instead, a wetting front detector, developed in Australia and known as ‘FullStop’, was recommended to farmers (CSIRO, 2007).

Salinity

In a review of the sensitivity of crops to salinity, Ayers and Westcot (1985), using the best available information, classified mango, on a four-grade scale,[2] as being ‘sensitive’ to salinity. Based on the results of a four-year field experiment (1996–1999) in a mature

Figure 8.8 Young (six months) mango trees (cvs. Kent and Palmer) irrigated with micro-sprinklers – Petrolina-PE, Brazil (LM). See also colour plates section.

mango orchard (12 years old) in south-east Spain, this classification was later challenged by Zuazo *et al*. (2004). Their results suggested that mango was more tolerant of salinity than the analysis by Ayers and Westcot (1985) suggested.

In this part of Spain, which includes the coastal provinces of Malaga and Granada, seawater intrudes into the groundwater, especially in dry years. When this saline water is used for irrigation, visible (and serious) damage occurs to the mango trees, the chloride ion being particularly harmful. In the experiment (Zuazo *et al*., 2004) mango tree performance (cv. Osteen) was evaluated for two rootstocks (Gomera-1 and Gomera-3). The yield responses to four levels of water salinity (from 1.02 to 2.50 dS m^{-1}) were compared, and the results presented in the form of a salt-tolerance model, as used by Maas and Hoffman (1977). This includes a threshold electrical conductivity value at which yield loss begins, followed by a linear regression, the slope of which is a measure of the rate of yield decline as salt levels increase. Although there were small differences between the two rootstocks (Gomera-1 was slightly more tolerant than Gomera-3), one salt-tolerance model fitted both sets of data. For the first two years, the threshold electrical conductivity of the saturated soil extract (EC_e) was 0.88 dS m^{-1}, but this increased to 1.81 dS m^{-1} in years 3 and 4 of the experiment. The corresponding slopes were 17.1% yield loss, for each unit increase in EC_e ($r^2 = 0.66$, $N = 48$), and 12.5% ($r^2 = 0.76$, $N = 48$). By extrapolation of the straight line, zero yields were predicted at EC_e values of 6.75 and 9.78 dS m^{-1}, respectively. With a leaching fraction of about 0.20, the corresponding values for the electrical conductivity of the irrigation water were 3.7 and 4.1 dS m^{-1}. Based on the Mass and Hoffman (1977) model, these parameters are characteristic of a crop that is at the interface between being classified as moderately sensitive or moderately tolerant to salinity (Zuazo *et al*., 2004)

Intensification

Like many tree crops, intensification is now the name of the game in the case of mango. Pioneering work in South Africa has highlighted some of the benefits that can result from ultra-high-density planting (Oosthuyse, 2009). This means planting trees in hedgerows at a spacing of 3 m (between rows) × 2 m (or even 1 m) between trees within a row. This corresponds to planting densities of 1666 trees ha^{-1} or 3330 trees ha^{-1}. This is very different from the traditional 10 × 10 m spacing (100 trees ha^{-1}) or even 10 × 5 m (200 trees ha^{-1}). With the ultra-high densities, it is important to restrict the size of the canopy, and to control canopy shape, by selective branch removal, and to keep the height of the trees below 2 m to facilitate easy manual harvesting of the fruit (and spraying). Other advantages of high-density planting include a reduction in the time taken from planting for the trees to reach the optimum canopy cover (therefore fewer weeds), and to come into full production (Oosthuyse, 2009). The system lends itself to drip irrigation and fertigation. This system of production is now being promoted in India (see the video: Sharma, 2012), where the emphasis is on the production of uniform high-quality fruit for export. The trees are mulched with coconut coir waste or with black plastic for weed control and water conservation.

Summary: water management

1. In the tropics, after the induction of flowering following a period of water stress, irrigation recommences when 75% of the canopy is in flower.
2. Micro-sprinklers and drip irrigation are probably the two most effective ways of irrigating mango.
3. A micro-dendrometer (which measures the diameter of a twig) has been successfully used to monitor the onset of water stress in mango, but is not suitable for scheduling irrigation commercially.
4. Mango is moderately sensitive/moderately tolerant of salinity. Rootstocks may differ in their sensitivity to salinity.
5. Intensification of mango production will increase the need for irrigation and affect the way the crop is managed.

Conclusions

Less than 25 years ago, Rao and Chacko (1989) wrote in a summary paper at an ISHS international symposium on mango: ‘Studies on water relations in mango trees (are) a topic totally neglected so far and (their) effect(s) on various aspects of growth and development of the trees need attention'. The question that naturally follows is, 'How much progress has been made since then?'

Some progress has been made in our understanding of the flowering process, specifically the role of water in the initiation of flowering of mango in the tropics, although the mechanisms responsible have yet to be fully understood. Similarly, some progress has been made in our understanding of the processes of gas exchange, and the sensitivity of stomata (conductance and photosynthesis) to the dryness of the air. The sap-flow method has proved to be a useful way of measuring transpiration of a mango tree, and attempts have been made to monitor water use in the orchard using a range of techniques. Unfortunately these experiments (and others on the water relations of mango) have not always been well reported. Some progress has therefore been made, but it is probably not something that the commercial grower would recognise as being helpful in the short/medium term. The big change is the intensification of production, specifically the increases in tree density. This will impact on the water relations and irrigation requirements of mango, and should be the focus of future research on this topic.

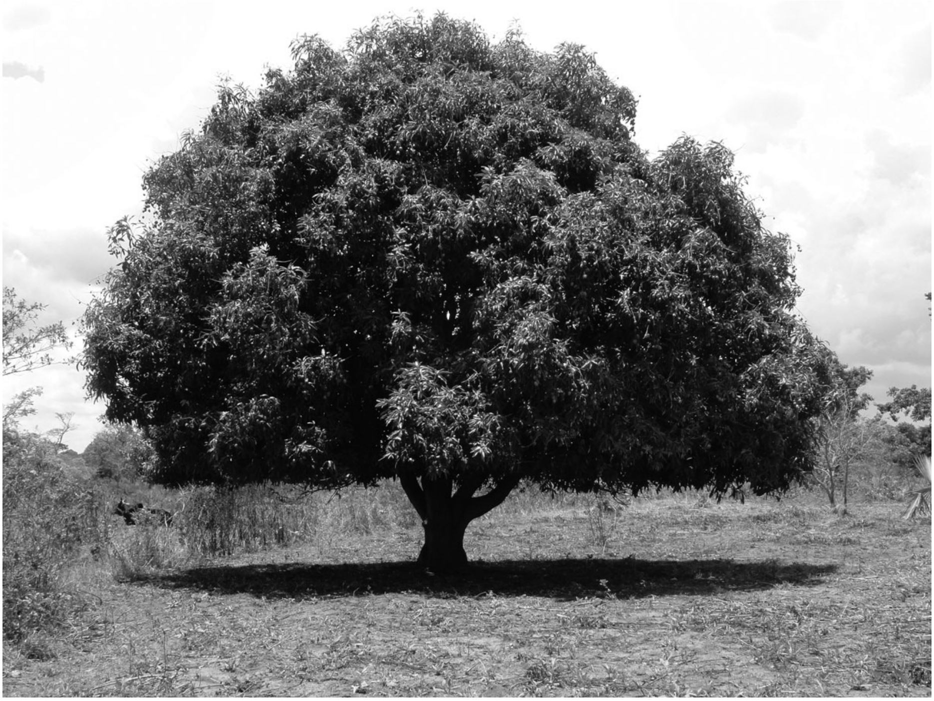

Figure 8.9 Mango: this long-lived tree is well adapted to a wide range of tropical and sub-tropical environments – Uganda (RCC). See also colour plates section.

Summary

The results of research on the water relations and irrigation requirements of the mango fruit tree are collated. The stages of development (including roots) are summarised, followed by reviews of plant–water relations, water requirements, water productivity and water management. This long-lived tree is well adapted to a wide range of tropical and subtropical environments (Figures 8.9 and 8.10). In the low-latitude tropics, flowering is initiated after a period of water stress (at least six weeks duration) is ended by rain or irrigation. In the high-latitude tropics and subtropics, flower buds are initiated during the cool winter months (<15 °C). Less than 1% of the flowers that set fruit reach maturity. Roots can reach depths of 5 m. Stomata occur on the lower leaf surface. They are sensitive to dry air, closing as the saturation deficit increases (from 0.5 to 4.0 kPa). In humid tropical areas, the mean seasonal ET_c rates average *c*. 4–5 mm d^{-1}, with peak rates of 5–6 mm d^{-1}. The crop coefficient (K_c) varies between 0.65 and 1.05. Water

Figure 8.10 Fresh mango for sale in Sierra Leone (RCC). See also colour plates section.

productivities are in the range 3–6 kg (fresh fruit) m^{-3} (irrigation). Micro-sprinklers and drip irrigation are the preferred methods of irrigation. The trend towards greater intensification of production will impact on the water relations and irrigation needs of mango and provides a focus for future research.

Endnotes

1 The latex exudate made it difficult to observe a clear end point when a pressure chamber was used to measure the xylem water potential.

2 Sensitive, moderately sensitive, moderately tolerant, tolerant.

9 Olive

Introduction

The olive (*Olea europea* L.) is native to the coastal areas of the eastern Mediterranean basin. These include south-east Europe, west Asia (including northern Iraq and northern Iran) and north Africa. For several thousand years the olive has been grown in the region surrounding the Mediterranean, mainly as a rain-fed crop. It is referred to several times in both the Bible and the Quran. Traditionally, the leafy 'olive branch' is known as a symbol of abundance, glory and peace, whilst olive oil has long been considered sacred.

Currently, Spain has the largest area (2.09 million ha), and is also the largest producer of table olives and olive oil (total 8.01 million t). It is followed by Italy (1.19 million ha; 3.17 million t), Greece (0.83 million ha; 1.81 million t), Morocco (0.74 million ha; 1.48 million t) and Turkey (0.83 million ha; 1.41 million t). Tunisia has a large area of olives (1.65 million ha), but low productivity (0.88 million t) due to the dry conditions. The largest producer in South America is Argentina, with 56 000 ha of olive yielding 170 000 t, whilst the USA with 14 000 ha produces 186 000 t. Of the estimated total of 9.5 million ha of olive orchards in the world today (producing 20.8 million t), two thirds (6 million ha) are still to be found in the Mediterranean region (FAO, 2012).

The vast majority of olives (over 90%) are grown for oil. This is used in catering and also in the textile industry, in cosmetics and in pharmacy. The trees also provide beautiful wood for carving. They can live for many hundreds of years, and will remain productive if well managed (Figure 9.1). The waste products after processing for oil are now being considered as a possible source of renewable energy. But, it is the expansion of olive oil production for culinary purposes, driven by health-related benefits, which is now boosting the industry. For centuries, olive oil has been treasured in Greece and other Mediterranean countries for its healing and nutritional properties, because of its high levels of monounsaturated fatty acids and polyphenolic compounds (Hu, 2003). This expansion is being achieved through both an increase in the planted area and also through intensification (within and beyond the Mediterranean countries), notably by changing from rain-fed to irrigated cropping systems, and by increasing the tree density. Intensification of table olive production began about 150 years ago, but it is only in the last 40–50 years that a more intensive approach has been adopted by the olive oil sector (Barranco *et al.*, 2010).

Although olive is considered to be drought resistant, it responds well to irrigation. Interestingly, recent bio-archaeological evidence has shown that the olive was being irrigated during the Middle Ages (ninth–fifteenth centuries) in southern France and

Figure 9.1 A very old olive tree! The olive has been grown in areas surrounding the Mediterranean for several thousand years – Jordan (HDT).

north-eastern Spain (Terral and Durand, 2006). In the last 15 years, the area of olives irrigated in Spain has increased from 200 000 ha to more than 400 000 ha, making it the main irrigated crop in that country (Villalobos *et al.*, 2012). This has been stimulated in part by the introduction of drip irrigation, but a scarcity of water means that using water to irrigate olives must be justified by good evidence of the economic benefits. To this end, recent research has focused on quantifying the yield responses to irrigation and, in particular, identifying the minimum amount of water required, rather than targeting maximum yields per unit area.

Plant densities have generally been increased from 100 trees ha^{-1} or less up to around 500 trees ha^{-1}, but there are also an estimated 100 000 ha of more densely planted orchards worldwide, where the trees are grown in hedgerows at densities of 1000–2250 trees ha^{-1}. These hedgerow trees can be harvested mechanically, but pruning is essential (Pastor *et al.*, 2008). A survey of olive growers in California, where olive oil production is expected to become a major agricultural commodity, revealed that there were about 4900 ha planted at densities between 1100 and 2240 trees ha^{-1} by the end of 2008. With one exception, all these growers used drip irrigation (Flynn and Mondavi, 2009).

New countries are now joining the olive industry. For example, New Zealand is looking to expand the production of high-quality, boutique-style oil for the export market. Currently, it is a very small producer (*c*. 250 ha). New olive orchards are being planted in marginal areas (alongside grapes) on light, free-draining soils. Irrigation is being applied to supplement low summer rainfall, but as elsewhere there is competition for the available water resources (Greven *et al*., 2009). The olive industry is also expanding in Australia, from virtually nothing in 1995 to 30 000 ha (71 000 t) in 2010 (Mailer and Ayton, 2011). Connor (2005) has questioned the 'transferability to Australian conditions of the information on olive physiology and adaptation that has accumulated in the Mediterranean countries'. Because the majority of the olive orchards in Australia are irrigated, the considered answer from Connor himself was 'relatively little'.

Because of the problems associated with water scarcity in nearly all the countries producing olives, a large number of (deficit) irrigation experiments[1] have been carried out in recent years in Spain (Ruiz-Sanchez *et al*., 2010) and elsewhere. Concurrent research has been directed at understanding how the olive responds and adapts to water stress. This activity has led to a proliferation of publications. In this chapter, the results of selected experiments are summarised, and an attempt is made to draw generic conclusions. Starting with a description of the stages of development (including roots) of the olive in relation to water availability, this chapter reviews plant–water relations, water requirements, water productivity and irrigation systems.

Several excellent reviews on water-related topics specific to the olive have been published, including one on its water use (Fernández and Moreno, 1999), its capacity to adapt to dry conditions (Connor, 2005), the physiology of yield development (Connor and Fereres, 2005) and the yield response to water (Fereres, 2012). Reference is made to all of these reviews here. In addition, there are two text books worthy of mention. The one by Therios (2009) covers all aspects of olive culture, whilst the second focuses, almost entirely from an Australian perspective, on the production and processing of table olives (Kailis and Harris, 2007).

Crop development

Commercial production of olive is possible throughout the warm temperate regions and especially in the dry subtropical or Mediterranean regions between latitudes 30° and 45° N. Land adjacent to the Mediterranean Sea with its dry summers, mild winters (temperatures not less than –8 to –6 °C for any length of time) and proximity to the sea (to protect trees from excessively high or low temperatures) is particularly suitable (Figure 9.2). Most commercial cultivars require a period of low temperatures to induce flowering (about 10 weeks with mean air temperatures below 12 °C). This prerequisite is known as the chilling requirement. The tree will grow, but not fruit in the tropics.

Olive is successfully cultivated without irrigation in areas where the average annual rainfall is >600 mm, but can survive with as little as 200–250 mm (Fereres, 2012). Olive growing has recently expanded, for example, into dry areas in north-western Syria

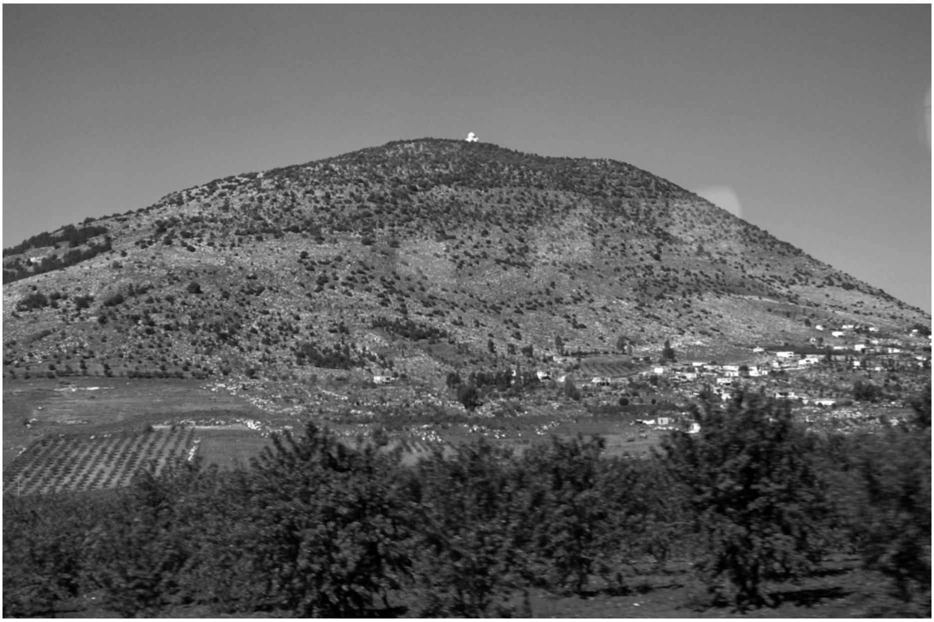

Figure 9.2 A traditional olive orchard – Israel (MKVC).

Figure 9.3 Olive trees being established in one corner of a rainwater harvesting plot where the runoff is concentrated and where barley-sheep farming systems prevail – Al Anbar desert, Jordan average annual (winter) rainfall *c*. 115 mm (MKVC).

(Khanasser Valley, 35° 49′ N 37° 29′ E), where traditional barley-sheep farming systems prevail and the annual rainfall is only 200–300 mm (Figures 9.3 and 9.4). Enterprising farmers looking to diversify their incomes planted olive trees in the valley. A water-harvesting trial was established in 1999 and planted with a local, drought-

Figure 9.4 A well-established olive orchard based on rainwater harvesting – Al Anbar desert, Jordan (MKVC).

Figure 9.5 A new olive orchard being established on overgrazed, degraded, stony ground at the foot of sloping land where runoff collects –Al Anbar desert, Jordan (MKVC).

resistant cultivar (Qaisi) on over-grazed, degraded, stony ground at the foot of sloping land (Figure 9.5). Tree growth was monitored over three years (2003–2005), when the annual rainfall averaged 208 mm, and the annual potential evapotranspiration rate (ET_o) was 1850 mm. Two to three rounds of irrigation (total 200–400 L tree^{-1}) were applied during the summer months (July to September) and these were supplemented by rainwater harvested (from runoff) during the rainy season (from October to May). The average annual depth of water ‘harvested’ from the micro-catchments (50 m^2 in area) was equivalent to 271 mm of rain. (The ratio of the area of the micro-catchment to the area of the tree basin was *c*. 32:1). The study confirmed that it was possible, with innovative rainwater management, to produce olives in arid areas on relatively shallow soils (up to 0.90 m deep) with little or no formal irrigation (Tubeileh *et al*. 2009).

Vegetative growth

The olive is a xerophytic evergreen tree that can attain a height of 8–15 m, but under cultivation it is kept at 4–5 m by pruning. The small, silvery-green leaves are thick and leathery with a waxy upper surface. The lower surface is protected by a mass of peltate hairs with numerous, sunken stomata (at densities of 420–540 stomata mm^{-2}) with small openings (*c*. 11 × 5 μm). Cultivars differ in the morphological and structural leaf adaptations to protect against water loss. This does not mean that the olive tree will not respond to irrigation, only that it is adapted to withstand drought (Hendrickson and Veihmeyer, 1949; Beede and Goldhamer 1994; Bacelar *et al*., 2004). A detailed review of the photosynthetic processes (C_3 pathway), at the leaf and canopy levels, has been prepared by Connor and Fereres (2005). The optimum temperature for net photosynthesis is about 28 °C.

The rate of expansion of the tree trunk is particularly sensitive to water stress. This sensitivity increases as the tree ages. Branch length is also sensitive to water stress in both young and mature trees. This means that the number of leaf nodes (which are where the flower buds form) is reduced. The amount of fruit on a tree also influences vegetative growth. For example, in the early years after field planting especially, a large fruit load will reduce both trunk and canopy expansion rates (Martin-Vertedor *et al*., 2011a). The length of time it takes for a tree canopy to develop depends in part on how the soil surface (whether it is cultivated or not) and any understorey vegetation (weeds, pasture or intercrops) are managed. There is always a risk of soil erosion on sloping land when the area between trees is cultivated. But, in a rain-fed orchard the risk of water stress increases with the size of the crop canopy (Connor, 2005; Villalobos *et al*., 2000; Martin-Vertedor *et al*., 2011a; Fereres, 2012).

Flowering

Flowers are born on inflorescences that, following a period of winter dormancy, develop in the spring from buds in the axils of leaves formed on wood produced during the previous year. The terminal bud on a shoot is nearly always vegetative. The flowers are either ‘perfect’ hermaphrodite, containing both male and female parts, or ‘imperfect’ staminate, capable of only producing pollen. In a controlled water-deficit experiment, Rapoport *et al*. (2011) found that water stress during winter dormancy had no lasting effect on the flowering process, recovery being rapid on re-watering. Water stress during inflorescence development reduced the number of inflorescences, the number of flowers and the number of imperfect flowers, and inhibited ovule development. Water stress during flowering and initial fruit set (spring and early summer) caused flowers to dry and abscise as a unit, exposing senescent stigmas, which were no longer receptive to pollination. The flowers are largely wind pollinated, but less than 2% of the flowers set fruit.

Fruiting

The fruit is a small drupe. It contains a single seed, known as a pit (USA) or stone (UK), which develops from at least one of four ovules present in the ovary. Fruit numbers are reduced when there are fewer flowers and/or fertilisation is inhibited. Increased size of individual fruits may not always compensate for any reduction in fruit number (Rapoport *et al*., 2011). Connor (2005) proposed a three-part explanation for successful oil production under severe water stress in Mediterranean environments. First, during the early stages of olive fruit formation (lasting about eight weeks) the tree can tolerate moderate water stress (pre-dawn leaf water potentials between –2 and –3 MPa) without much reduction in its potential to accumulate oil. Second, during the later stages of fruit development, carbon fixation by the fruit itself, together with the inherent capacity of the olive tree to use water efficiently, sustains limited growth, enabling the fruit to survive until, third, following rain in the autumn, the tree water status recovers rapidly and substantial quantities of new assimilate are produced (when even previously ‘wrinkled’ fruit will recover). It takes about 15–18 months from flower bud initiation to fruit ripening, including four to five months for fruit filling (Figure 9.6). The pulp-to-pit ratio is an important quality criterion for both table and olive oil fruit (Connor, 2005).

The components of yield for olive oil can be summarised as follows:

$$\text{Oil yield } (\text{kg tree}^{-1}) = \frac{\text{Number of fruits } (\text{tree}^{-1}) \times \text{Mean fresh fruit weight (g)} \times \text{Oil content } (\%\text{ fresh weight})}{1000}$$

Irrigation may increase the fresh weight of an individual fruit, but may reduce the oil concentration of the mesocarp, which, depending in part on the cultivar, may result in a reduction in the oil yield. Oils accumulate during the late summer and autumn. The final oil content also has implications on the costs of processing. For table olives, fruit size is important. A reasonable commercial yield of fresh fruit from a rain-fed crop is 2–5 t ha^{-1} and from an irrigated crop 12–15 t ha^{-1} (averaged over two years, to allow for on–off syndrome, see below). Oils from irrigated orchards are usually less bitter and pungent than those from rain-fed areas (Fereres, 2012).

Fruits are distributed irregularly in the canopy. They are formed preferentially on the illuminated sides of the canopy, namely the top and southern sides in the Northern Hemisphere. Pruning practices in an olive orchard are designed to allow light to penetrate into the canopy and to promote fruiting sites (Barranco, *et al*., 2010). The design of hedgerow systems to facilitate mechanisation, whilst optimising the

Figure 9.6 Olive fruits. It takes about 15–18 months from flower bud initiation to fruit ripening, including four to five months for fruit filling – France (MKVC). See also colour plates section.

interception and distribution of incident solar radiation over the canopy, has been the subject of detailed research by Connor (2006) and Connor *et al.* (2012).

Olive has an alternate bearing pattern whereby fruit production fluctuates between large and small yields in alternate years. These are often called 'on' and 'off' years. Cultivars differ in the degree to which biennial bearing occurs. As fruits are formed on last year's wood, excess vegetative growth in one year can lead to a high fruit yield the next, but less vegetative growth (because of competition for assimilates). This, in turn, means a low yield in the following year. In this way biennial bearing is initiated. The issue is further complicated when mature trees are pruned to reduce vegetative growth. Without management interventions the 'yield ratio' (ratio of yield in 'on' years to that in 'off' years) can be as much as 10:1 (Martin-Vertedor *et al.*, 2011a).

Roots

Little research into the root distribution and root activity of olive trees has been reported. In general terms, Fereres (2012) described the root system of olive as being 'extensive and vigorous', with most roots found in the top 1 m of soil, although they can extend to depths of 2–3 m in deep alluvial soils. In California (USA), Hendrickson and Veihmeyer (1949) recorded water extraction by roots of unirrigated olive trees (cv. Manzanillo; 25 years old, spaced 9.1 × 9.1 m or 120 trees ha^{-1}), growing in a sandy loam soil, from depths of at least 1.8 m.

Apart from observations such as these, very little systematic research on the actual distribution and dynamics of the root system of the olive tree appears to have been published. Exceptions include a detailed investigation by Fernández *et al.* (1991) in Spain. They traced roots of previously unirrigated, 20-year-old trees (cv. Manzanillo) to depths of 2 m and at distances greater than 2.5 m away from the trunk (trees spaced 7 × 7 m, sandy loam soil). Root densities with drip irrigation were recorded, but the data, as presented, are not easy to interpret or to summarise. The greatest root density occurred in the wetted areas, down to a depth of 0.6 m, the most abundant being roots with a diameter <0.5 mm. Root length densities were also monitored in three commercial orchards in north-west Argentina in relation to different drip irrigation emitter arrangements. Approximately 70% of the root system (cv. Manzanillo) was concentrated in the 0–0.50 m (sandy) soil layer, and most of the roots were within 0.50 m of the drip line. The total root length per unit leaf area averaged 1.8–3.5 km m^{-2} across the three sites (Searles *et al.*, 2009). This research was done in an area with very low rainfall so that the soil away from the influence of the emitters was dry, which explains why there were so few roots outside the wetted zone.

A recent paper by Polverigiani *et al.* (2012) describes the results of observations made in a rhizotron (a glass window 0.8 m deep and 1.3 m wide, situated 0.5 m away from the trunks of four drip-irrigated trees) over a 10-month period (November 2007 to August 2008) in central Italy (43° 29′ N 13° 07′ E). Root growth (extension) continued throughout the winter (November to mid-March). The growth of very fine (<0.2 mm) roots peaked in February, and fine roots (>0.2 mm), to a lesser extent, in April/May. (For the same mass, very fine roots have 1.55 times the surface area of fine roots). During the summer, from mid-June to late August, root growth virtually ceased. At this time, the average daytime temperature was 25.4 °C, shoot extension was rapid and the fruits were expanding and ripening. Both shoot and root processes were competing with the fruits for assimilates. Root mortality was first observed in late April, peaking in May. Mortality declined with increases in soil depth.

The proportion of the total biomass partitioned to the roots has been estimated to be about 0.26–0.30 (Connor and Fereres, 2005).

Cultivars

There are at least 2000 recognised olive tree cultivars, but only a few are grown on a large scale (Barranco *et al.*, 2010). The ones listed in Box 9.1 have been the subject of research summarised in this paper (see oliveaustralia, 2012 for details; FAO, 2005).

Summary: crop development

1. The olive is an evergreen, xerophytic tree, well adapted to survive dry conditions. Stomata are only found on the lower surface of leaves.

Box 9.1 Olive cultivars referred to in the text (abstracted in part from: oliveaustralia, 2012 and FAO, 2005).

- *Arbequina:* commonly grown in north-east Spain, good for eating and for oil.
- *Barnea:* a modern, dual-purpose cultivar, bred in Israel.
- *Chemlali de Sfax:* grown for oil, from north Africa, very popular in Tunisia.
- *Coratina:* grown for oil, popular in Italy.
- *Cordovil:* table olive, popular in Portugal.
- *Frantoio*: grown for oil, popular in Tuscany, Italy.
- *Kalamata:* a large, black table olive from Greece.
- *Koroneiki:* a small olive, source of high-quality oil, from Crete, Greece.
- *Leccino:* widely grown for oil, originated in Tuscany, Italy.
- *Manzanillo:* widely grown, large purple-green olive, rich taste, prolific yielder, from southern Spain.
- *Meski:* grown for the table, popular in Tunisia.
- *Morisca:* one of the most important cultivars in south-west Spain and Portugal, it is biennial (bearing fruit in alternate years) and also very vigorous, producing excessive vegetative growth, which is controlled by pruning.
- *Muhasan:* grown on a wide scale in Israel, Palestine and Jordan under both irrigated and dry land conditions; prone to biennial bearing.
- *Picual:* one of the most widely cultivated table olives in Spain.
- *Picholine:* grown in the south of France, green fruit.
- *Proline:* sensitive to salinity.
- *Qaisi*: drought tolerant, from Syria.
- *Sevillano:* high-quality table olive, takes second place to Manzanillo in both Spanish and Californian table markets.
- *Verdale:* from the south of France, found in many different forms around the world, popular in Australia.

2. Commercial production of olive is possible throughout the warm temperate regions and especially in the dry subtropical or Mediterranean regions. The olive is responsive to irrigation.
3. For successful cultivation the minimum average annual rainfall needed is about 600 mm. Olives can survive with 200–250 mm. Rainwater harvesting is an alternative to formal irrigation.
4. A period of low temperatures (*c*. 10 weeks at less than 12 °C) is required to induce flowering.
5. Flowers are born in the spring on inflorescences that develop from buds in the axils of leaves formed on wood produced the previous year. Less than 2% of flowers set fruit.
6. It takes from 15–18 months from flower bud induction to fruit ripening.
7. The olive tree is prone to biennial bearing, which complicates experimentation.
8. There has been little research reported on root systems of the olive tree, but roots can extend to depths of at least 2 m; root growth virtually ceases during the summer.

Plant–water relations

Olive leaves are well designed to control water loss. Morphological characteristics allow minimum radiation load (small size, high reflectivity and dominant vertical display) and maximum heat exchange, whilst the stomata, which are covered by a dense network of trichomes, provide a very effective control of transpiration (Connor, 2005).

Additional safeguards that protect the olive tree against the adverse effects of drought include:

- Narrow xylem vessels with low hydraulic conductivity reduce risk of embolism (cavitation created from micro-bubbles).
- Osmotic adjustment allows a positive pressure (turgor) to be maintained in the cells.
- Abscisic acid (a phytohormone) may play an important role as an endogenous messenger influencing the response of the tree to drought.
- Aquaporins (proteins) may facilitate the flow of water across cell membranes by increasing their hydraulic conductivity.
- Proline (an amino acid) is an important component of the response mechanism of the olive to water stress.
- In addition, the following attributes of the leaf all contribute to the protection against water loss: low water content when a leaf is saturated, large wax content that increases diffusion resistance of the cuticule, specialised cells at the base of the peltate (trichome) stalks and the dense packing of mesophyll cells (Fernández *et al*., 1997; Sebastiani, 2011).

The results of some of the many recent experiments on the water relations of the olive are summarised below under the subheadings: plant water status and gas exchange, trunk diameter variability and osmotic regulation. Each country in which research is undertaken is considered in turn, beginning with Spain, the lead country, under these headings, followed by the other countries in alphabetical order.

Plant water status and gas exchange

The leaf (or stem) water potential is commonly measured with a pressure bomb, with readings taken immediately before dawn and/or at midday. Leaf water potential is measured on exposed leaves, whilst for stem water potential the leaves are shaded. The stem water potential is a much more stable indicator of the water status of mature trees than leaf water potential (Fereres, 2012). Sap flow sensors are used to monitor changes in sap speed, which is an indirect measure of transpiration in individual trees. Displacement sensors (dendrometers) are used to monitor trunk diameter fluctuations, which are considered to be early indicators of water stress. All three of these techniques (pressure bomb, sap-flow sensors and dendrometers, together with leaf diffusion porometers) have been used in research projects with the olive tree. Typical reference values of stem water potentials are listed in Table 9.1.

Table 9.1 Typical values of stem water potential (MPa) at different levels of water stress on sunny, summer days ($ET_o = 5–6$ mm d^{-1}), based on Fereres (2012)

	Pre-dawn	Midday
Well-watered	> –0.5	–1.0 to –1.2
Moderate stress		–1.7 to –2.5
Severe stress		–3.5 to –4.0
Extreme stress		–7.0 to –8.0

Spain

Diurnal measurements of leaf water potential and stomatal conductance at different times during the season in south-west Spain (37º 17′ N 06º 03′ W; alt. 30 m) showed how olive trees (26 years old; cv. Manzanillo) conserved water under conditions of high evaporative demand (saturation deficit up to 3.5 kPa) by closing their stomata (Fernández *et al.*, 1997). The stomata on young leaves exhibited better water use control than those on leaves that had been on the tree for a year. Maximum stomatal conductances occurred at relatively low photon flux densities (*c*. 500 μmol m^{-2} s^{-1}). At similar radiation levels and saturation deficits, the stomata were wider open in the morning than in the afternoon. In well-irrigated trees, pre-dawn leaf water potentials never fell below –0.50 MPa, but reached –2.47 MPa at midday late in the season. The corresponding values for unirrigated trees were less than –1.60 MPa and – 3.63 MPa respectively. After watering, both these variables matched those of irrigated trees within two days.

In order to characterise with greater precision the gas exchange processes of olive trees at various levels of water stress, Moriana *et al.* (2002) took measurements within a deficit irrigation experiment in Cordoba (38° N 4.8° W; alt. 110 m) during 1998 (trees spaced 6 × 6 m = 280 trees ha^{-1}). Both leaf photosynthesis and stomatal conductance responded diurnally and seasonally to changes in the tree water status and to the evaporative demand in similar ways (there was a close linear correlation between these two variables, $r^2 = 0.92$). Maximum values again occurred in the morning, followed by a continuous decline throughout the afternoon. As water stress increased, both the daily maximum and minimum values fell. In the absence of water stress, midday photosynthesis rates and stomatal conductances were high during the autumn and low on days when the air was dry (large saturation deficits). Transpiration efficiencies (mmol CO_2 (mol $H_2O)^{-1}$) followed a diurnal course similar to those for photosynthesis and stomatal conductance. At stem water potentials greater than –4 MPa, an inverse hyperbola described the relationship with the saturation deficit of the air ($R^2 = 0.91$). Stem water potentials fell to –8 MPa in the rain-fed treatment, which is a much lower value than those observed in most crop plants subjected to drought (Moriana *et al.*, 2002). This capacity of the olive tree to reduce its stem water potential to such low levels explains why it was able to extract water from the 2.4 m deep soil profile (192 mm) in the rain-fed plots at water contents below the conventionally accepted definition of permanent wilting point (soil matric potential = –1.5 MPa), also known as the lower limit of extraction (available water-holding capacity = 150 mm).

As part of a modelling study to predict photosynthesis under drought conditions, the photosynthesis capacity was observed to decline over the growing season in both irrigated and unirrigated olive trees (cv. Manzanilla). The seasonal reduction in leaf nitrogen content (on a leaf-area basis) was used in the model to predict photosynthesis under drought conditions (Diaz-Espejo *et al.*, 2006).

Previously, Jorba *et al.* (1985) had described the results of a container experiment at the University of Barcelona, Spain. In well-watered plants, leaf water potentials fell from –0.7 MPa at sunrise to –2.5 MPa at midday. Under dry conditions values as low as –4.0 MPa were recorded. There was a linear relationship between the net photosynthesis rate and leaf water potential over the range –1.0 to –3.5 MPa. The three cultivars studied (Arbequina, Manzanillo and Sevillana) all responded to dry conditions in similar ways. In another container experiment leaf conductance was found to be more sensitive to water stress than vegetative growth (Gomez-del Campo, 2007).

At the same site in south-west Spain referred to above, Fernández *et al.* (2006) subsequently compared the effects of 'partial root-zone drying' and 'regulated deficit irrigation' on various water status indicators, including leaf water potential, stomatal conductance and net CO_2 assimilation rates. No evidence could be found to show that partial root-zone drying, which involved keeping half the root zone dry for two to three weeks prior to switching the irrigation from one side of the tree to the other, had a positive effect on any of these variables compared with regulated deficit irrigation. In many species, for example the vine, allowing part of the root zone to dry in this way initiates a signalling mechanism. This triggers partial stomatal closure, which in turn reduces water loss by transpiration, without a proportional loss in yield. For olive, sap-flow measurements confirmed that daily water consumption was similar in both deficit irrigation treatments on most days throughout the irrigation period. There was no evidence to show that alternating the water application (by drip) from one side of a tree to the other had any advantages compared with conventional regulated deficit irrigation.

As a result of small reductions in stomatal conductance, trees with part of the root system in a drying soil maintained midday leaf water potentials at levels similar (*c.* –1.5 MPa) to those in trees in which the whole soil profile was kept close to field capacity (Torres-Ruiz *et al.*, 2011). However, in rain-fed trees, large reductions in stomatal conductances did not prevent midday leaf water potentials (between –3.5 and –5 MPa) from falling below those of the irrigated trees (–1 to –2 MPa).

In a complex study, conducted at two contrasting sites, Moriana *et al.* (2012) attempted to evaluate the possibility of using stem water potential as a guide for scheduling irrigation. The results are not easy to summarise, since the responses varied with site and season. This was an ambitious project, but the practical outcomes are not immediately obvious.

The presence of fruit on an olive tree influences its water status. For example, in an experiment in south-west Spain at mid-morning, stomatal conductances (cv. Morisca) were about 17% greater during late summer and early autumn, that is from a few weeks after fruit set until harvest, in trees with fruits than in those without. This response was observed at all levels of water supply (Martin-Vertedor *et al*., 2011a). The lowest midday leaf water potentials recorded were about –4.0 MPa in young trees and –3.0 MPa in mature trees, both recorded in the early autumn. Leaf water potential values were less in trees with a medium/heavy fruit load than in those without fruit.

In recent years, the so-called ‘magnetic leaf-patch clamp pressure-probe’ has been successfully used to measure the pressure potential (turgor pressure) within a leaf. A series of papers demonstrate how this new sensor (known commercially as a ZIM probe) has the potential to monitor on a continuous basis the water status of olive trees in an orchard (Fernández *et al*., 2011c; Rodriguez-Dominguez *et al*., 2012).

Italy

In southern Italy (41° 06′ N 14° 43′ E; alt. 250 m), Tognetti *et al*. (2004) made a sequence of measurements in a field experiment. Diurnal changes in sap flow (compensation heat-pulse technique), leaf water potential and stomatal conductances were recorded between May and October 2002 in an 11-year-old orchard (cv. Kalamata grafted on DA121 rootstock; tree spacing 3×6 m = 555 trees ha^{-1}) on irrigated and rain-fed trees. Pre-dawn leaf water potentials never fell below –0.5 MPa in irrigated trees, or below –2.5 MPa at midday. Both these values were very close to those reported in Spain. Sap-flow rates for irrigated trees peaked at midday, reaching maximum values of 4–5 kg h^{-1} in June before progressively declining until October. Mean daily stomatal conductance also declined as the summer progressed. There was a positive linear relationship ($r^2 = 0.83$, irrigated trees) between hourly sap-flow rates and the saturation deficit of the air (range 0 to 3.5 kPa). Similarly, there was a linear correlation ($r^2 = 0.72$) between daily sap flow and daily estimates (Penman–Monteith equation) of reference crop evapotranspiration (ET_o, range 0 to 6 mm d^{-1}). The hydraulic conductivity of a tree (represented by the slope of the line relating xylem water potential and sap flow) declined from June onwards, more in the rain-fed trees than in those that were irrigated. A polynomial quadratic curve represented the close relationship between the photosynthetic rate and stomatal conductance ($R^2 = 0.87$).

Morocco

In a ‘partial root-zone drying’ field experiment in Morocco (31° 38′ N 08° 04′ W) with mature olive trees (spaced 6×6 m = 280 trees ha^{-1}), Centritto *et al*. (2005) found, when similar depths of water were applied, that the leaf water status in trees (irrigated on alternate sides) was similar to that recorded in the control trees (irrigated on both sides). By contrast, applying half that quantity of water on one side of the tree only and switching sides every two weeks, reduced the leaf water potential, but only marginally, relative to the 50% water saving. The relative water contents of the leaves were similar, and their photosynthetic capacity was maintained. Wahbi *et al*. (2005) have described the yield responses in this experiment (see below).

New Zealand

In New Zealand, Greven *et al*. (2009) investigated the impact of short-term water stress on some physiological processes in five-year-old trees (cv. Verdale) growing in a stony silt loam soil with a water-holding capacity of only about 70 mm m^{-1}. Roots did not extend below a depth of 1 m. Using the compensation heat-pulse technique, sap-flow rates were monitored regularly over a two-month period. On warm, sunny days, these peaked in irrigated trees at about 3 L h^{-1}, equating to 30 L d^{-1} $tree^{-1}$, whilst the corresponding flow rates in adjacent trees without irrigation, or significant rainfall, for two months declined to 0.4 L h^{-1}. Leaf water potentials in irrigated trees varied between –0.4 MPa at dawn and –2.1 MPa at noon, whilst stem water potentials did not fall below –1.4 MPa. In unirrigated trees, pre-dawn leaf water potentials declined to less than –4.0 MPa, a very low value that was below the limit of measurement. Upon re-watering, the recovery in sap flow rates was rapid (within seven days) whilst, because of variability between leaves on the same tree, it took up to 10 days for leaf water potentials to return to pre-drought levels. This is unusual for tree crops, as normally it is the opposite way round, with recovery in water status preceding the recovery in transpiration rates.

Tunisia

In southern Tunisia (34° N 10° E), Masmoudi *et al.* (2010) recorded midday leaf water potentials and stomatal conductances in five cultivars of six-year-old olive trees over a summer season. There were three deficit irrigation treatments (20, 50 and 100% ET_c replacement, where ET_c is the potential water use by olives). Due to variability in the data, it is not easy to interpret the results presented. Although there were seasonal and cultivar differences, the responses to the irrigation treatments were inconsistent. Early in the summer, cv. Pincholine had the highest leaf water potentials under both wet (–0.97 MPa) and dry (–1.5 MPa) soil conditions. The corresponding values for the other cultivars were lower (range –1.63 to –2.13 MPa). Later in the season, the leaf water potentials were least for cv. Coratina (–4 MPa), compared with –3 MPa for the other four cultivars. Masmoudi *et al.* (2010) stated that the recommended threshold stem water potentials at midday for initiating irrigation of olives in central Spain were –1.2 MPa during 'on years' and –1.4 MPa during 'off years'. It is not clear on what evidence this assertion was based.

Surprisingly, diurnal changes in leaf conductance were judged to be more consistent than leaf water potentials (since sometimes it was difficult to judge when the end point occurred in the pressure bomb). In all cases (cultivars and watering levels), there was evidence of (partial) midday stomatal closure. Conductance fell during the morning, reaching minimum values around midday, before increasing again during the afternoon. There were significant differencies in stomatal conductance between cultivars and also between the irrigation deficit treatments (Masmoudi *et al.*, 2010). This was not an easy paper to follow.

The main observation that came out of another deficit irrigation experiment in an arid region of Tunisia (34° 43′ N 10° 41′ E) was the adverse effects of high temperatures during the summer on photosynthetic rates for both irrigated and rain-fed trees (cv. Chemlali). Mean monthly maximum daily temperatures were 34.5 °C (June), 37 °C (July) and 39 °C (August). It was not until the weather cooled in September and October (31 °C) that the gas-exchange processes (stomatal conductance, photosynthesis and transpiration) in the irrigated trees returned to values recorded in the spring. The more severe the water stress experienced, the slower the rate of recovery. On a diurnal basis in

June, the stomata were partly open early in the morning, but from 0800 h onwards there was progressive stomatal closure for the remainder of the day. A detailed analysis showed that for an irrigated tree the optimum temperature for photosynthesis was 30 °C (corresponding to a photosynthetically active radiation intensity of 1250 µmol m^{-2} s^{-1}), declining rapidly to almost zero at 40 °C. For a severely water-stressed tree the temperature response curve was largely flat, at a low photosynthetic rate, before peaking at about 28 °C. The authors (Ahmed *et al.*, 2007) refer to the response of the olive to conditions in the summer period as 'a rest phase'.

Trunk diameter variability

Reports of olive trunk diameter variability use a number of terms which are defined here (Box 9.2) in an attempt to minimise confusion.

Spain

During 2009, the usefulness of maximum trunk diameter measurements to detect water stress in mature, 12-year-old olive trees (cv. Arbequina), heavy with fruit, was studied in a commercial orchard in south-west Spain (37° 30′ N 05° 44′ W; alt. 60 m) by Fernández *et al*. (2011a). There were two treatments: one in which the soil was irrigated to field capacity twice a week, and another in which the soil was allowed to dry until the fruits were observed to shrivel, whereupon the same cumulative total quantity of water was applied as in the first treatment. In addition there were two control trees that were supplied with excess water ($1.5ET_c$) to ensure that they were never short of water. The potential crop water use (ET_c) was determined using this relationship:

$$ET_c = K_c \times K_r \times ET_o$$

Box 9.2 Definitions of terms used when monitoring variability in tree trunk size

Trunk diameter variation: the generic term from which other indicators of water stress are derived.
Maximum daily shrinkage: maximum trunk diameter minus minimum diameter, calculated on a daily basis.
Daily recovery: maximum trunk diameter on a particular day minus minimum diameter on preceding day
Trunk growth rate: usually measured over a series of days; can be expressed as daily growth.
Daily growth rate: equates to trunk growth rate.
Signal intensity: actual daily shrinkage divided by reference daily shrinkage.
Sensitivity: a measure of precision; in this case, signal intensity divided by coefficient of variation.
Actual/reference values: actual value of variable for deficit-irrigated trees divided by reference value for well-watered control trees.

where ET_o is the reference crop evapotranspiration, K_c is the crop coefficient (based on Fernández *et al*., 2006) and K_r is a canopy coefficient related to ground cover (Fereres *et al*., 2012)

The 'trunk diameter variations' were analysed by Fernández *et al.* (2011a) in a number of different ways with the overall aim of identifying an index that could usefully and reliably identify water stress in an orchard in south-west Spain. They found that the most useful approach was to calculate, on a daily basis, the difference between the maximum trunk diameter in a control well-watered tree, and that of the tree under comparison. This is referred to as the 'maximum trunk diameter difference'. Its value mimicked closely changes in the water status of the soil and plant, in contrast to the so-called signal intensity for 'maximum daily shrinkage' (= actual value/reference value) with which it was compared. For each comparison, four instrumented trees were enough to provide reliable data from which to detect the onset and severity of water stress for olive trees with a heavy fruit load (cv. Arbequina).

In a similar comparison, again in Spain, of the different ways in which 'trunk diameter variations' can be expressed (Box 9.2), Cuevas *et al.* (2010) came to the conclusion that, for trees with large root zones (low/medium planting density, old trees), the various derived indices were of little value where the aim was to keep the soil profile close to field capacity. However, the 'maximum daily shrinkage' and 'daily recovery' indices could be useful indicators to avoid fruit shrivelling, since this can adversely affect oil quality. In the same study, good relationships (linear) were obtained, for well-watered trees, between 'maximum daily shrinkage' and maximum daily air temperature (r^2 = 079–0.81), and also with the maximum daily saturation deficit of the air (r^2 = 0.74–0.80).

According to Moriana *et al.* (2000), the relationship between the maximum daily shrinkage and stem water potential had two components. Under conditions of mild water stress (stem water potential at midday above –1.5 MPa) the response was linear, i.e. the maximum daily shrinkage increased as the stress level increased. But, at stress levels greater than –1.5MPa, the maximum daily shrinkage got less. In other words, there was not a straightforward relation between these two parameters. However maximum daily shrinkage and weather variables such as temperature (in particular) and the saturation deficit of the air were correlated. Moriana *et al.* (2011) analysed daily weather and trunk shrinkage data, collected over four successive years (2005–2008), from fully irrigated, 37-year-old trees (cv. Manzanillo). Data from the fifth year (2009) were used to validate the relationships. The best correlations (all were linear) were between the maximum daily shrinkage of the trunk and the air temperature at midday (very highly significant, r^2 = 0.85; range *c.* 16 to 40 °C) and between the maximum daily shrinkage and the saturation deficit of the air (range 0 to 6 kPa), also at midday (r^2 = 0.81). There were seasonal differences in the relationships: the slope and/or intercept varied. But, for years when the fruit loads ('on' years and 'off' years) were similar, the correlations were also similar. It was expected that benchmarks of this nature would help facilitate the use of plant-based indicators as tools to improve irrigation-water management.

In a further attempt to develop plant-based indices for detecting the onset and severity of water stress in mature olive trees with a heavy fruit load, Fernández *et al.* (2011b) analysed the relations between sap flow, trunk diameter variation, midday stem water

Figure 1.2 An oasis in north-east Nigeria bordering Niger. The date palm (*Phoenix dactylifera* L.) (together with the branched doum palm (*Hyphaene thebaica* L. Mart)) relies on a shallow water table (or irrigation) for survival in these arid areas (MKVC).

Figure 1.5 Rambutan (*Nephelium lappaceum* L.) is native to Indonesia and Malaysia, and is a relatively common crop in South-east Asia The word 'rambut' refers to the spiky rind. Rambutan is related to the lychee (Chapter 6) – Thailand (HDT).

Figure 1.6 The purple mangosteen (*Garcinia mangostana* L.) is a tropical evergreen fruit tree believed to have originated in the islands of Indonesia. It is grown principally in South-east Asia and more recently it has been introduced into South America – Thailand (HDT).

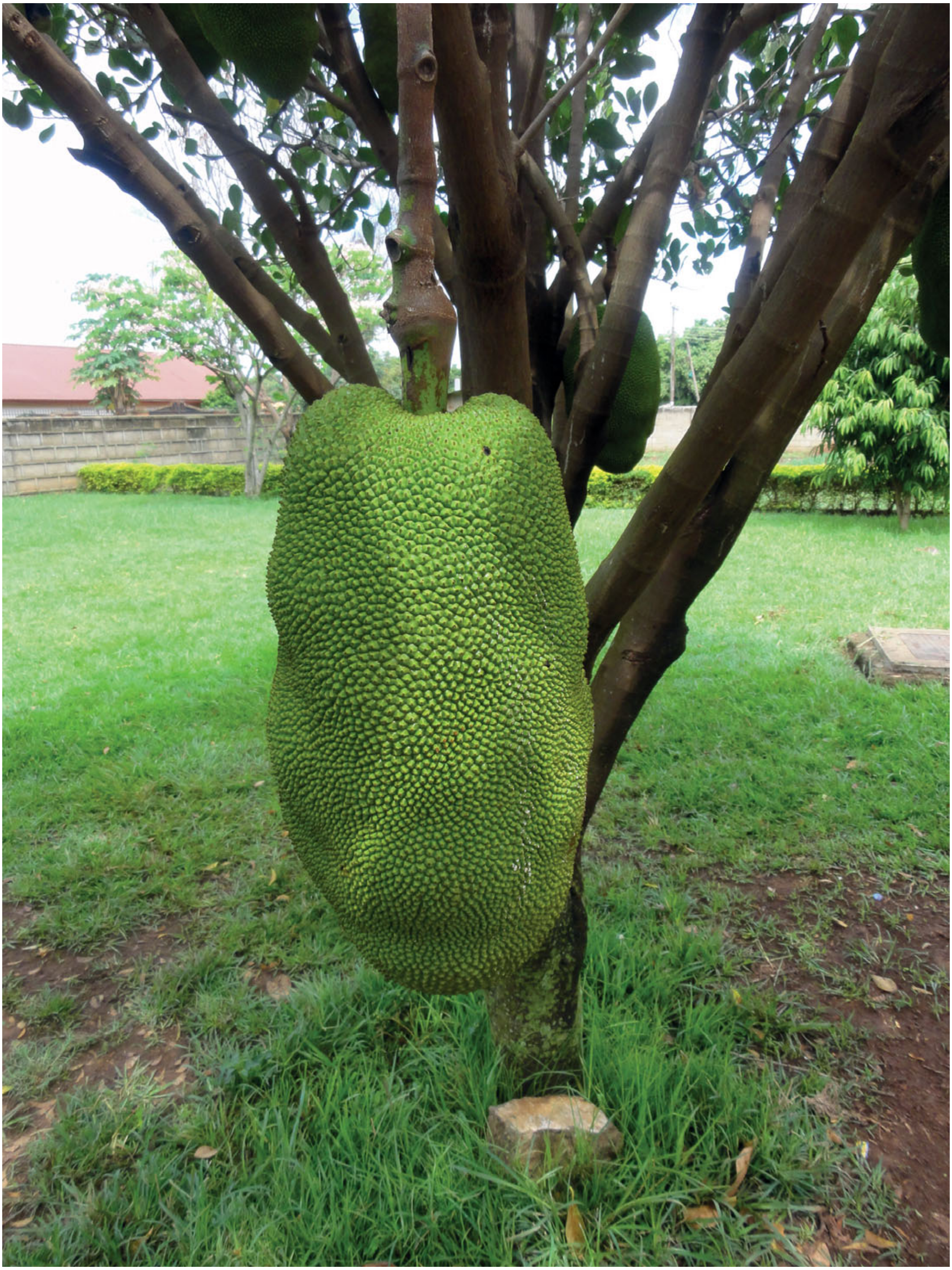

Figure 1.7 Individual fruits of jackfruit can weigh up to 30 kg and a productive tree can produce up to 200 fruits a year – Uganda (RCC).

Figure 1.13 Pineapples for sale in a supermarket in Beijing, China (MKVC).

Figure 1.14 Tapping for palm wine in Sierra Leone; palm trees can be a source of alcohol (RCC).

Figure 1.15 A small mixed rain-fed farm in Kenya with fruit trees (papaya and citrus) and arable crops (*Phaseolus* beans and maize) – (MKVC).

Figure 1.16 An example of a modern, intensive, hedgerow pear (*Pyrus communis* L.) orchard in New Zealand (with plastic cover) – (MKVC).

Figure 1.17 Palms have many ancillary products in addition to their fruit. Here, a Fulani cattle herder in northern Nigeria is seen weaving the fibres taken from a doum palm (*Hyphaene thebaica* L. Mart.) and creating ropes, mats, baskets and hats – (MKVC).

Figure 2.1 An avocado grove in the coast hills of Central California (EF).

Figure 2.4 Avocado fruits: under favourable conditions more fruits are set than the tree can support – Papua New Guinea (HDT).

Figure 2.6 Avocado fruit (cv. Hass), botanically a berry, is rich in vitamin D and, to a lesser extent, vitamins C and B. This variety was developed and selected in California – Tanzania (TCEC).

Figure 3.1 Cashew is grown principally for its nutritious kernel, the edible part of the nut – China (MKVC).

Figure 3.2 A young cashew tree – Malaysia (HDT).

Figure 3.5 The swollen pedicel known as the cashew apple is a source of juice high in vitamin C – Sierra Leone (RCC).

Figure 4.3 Red-fleshed sweet orange. Citrus fruits are a special type of berry with two distinct regions, the pericarp, or peel, and the endocarp, the juicy pulp, which is edible – Ethiopia (HDT).

Figure 4.6 Irrigation can increase the marketable size of citrus fruit – Botswana (HDT).

Figure 4.7 Newly planted citrus orchard in southern California with border-strip flood irrigation (MKVC).

Figure 4.10 Harvesting densely planted citrus – Seville, Spain (EF).

Figure 5.1 The date palm (*Phoenix dactylifera*) is one of the oldest known fruit crops. It is subtropical in origin and cultivation – northern Nigeria (MKVC).

Figure 5.3 An oasis in north-eastern Nigeria close to Niger border with mixed arable and palm tree crops (MKVC).

Figure 5.5 The much branched date palm inflorescence is a cluster of 8000–10 000 individual flowers. This forms in the axil of a leaf that developed in the previous year. The inflorescence is enclosed in a deciduous hard fibrous cover – Nigeria (MKVC).

Figure 5.6 The date fruit is a berry, with a single seed. The fruits are borne in clusters known as bunches – California, USA (MKVC).

Figure 6.1 The outside of the lychee fruit is covered by a pink-red, rough rind that is inedible, but easily removed to expose the sweet, translucent white flesh – Israel (RS).

Figure 7.1 Macadamia is the only important commercial food crop indigenous to Australia. It originated along the fringes of rainforests like these found in coastal north-eastern Australia (MKVC).

Figure 8.5 Mango tree with fruit. The mango fruit is a large fleshy drupe containing edible mesocarp. It is very variable in terms of size and shape, and the colour at maturity is cultivar-dependent – Sierra Leone (RCC).

Figure 8.6 Mango tree with fruit. Many fruitlets form on each panicle, but more than 80% are shed (fruit drop) during the first four weeks after fruit set – Sierra Leone (RCC).

Figure 8.8 Young (six months) mango trees (cvs. Kent and Palmer) irrigated with micro-sprinklers – Petrolina-PE, Brazil (LM).

Figure 8.9 Mango: this long-lived tree is well adapted to a wide range of tropical and sub-tropical environments – Uganda (RCC).

Figure 8.10 Fresh mango for sale in Sierra Leone (RCC).

Figure 9.6 Olive fruits. It takes about 15–18 months from flower bud initiation to fruit ripening, including four to five months for fruit filling – France (MKVC).

Figure 9.7 High-density, drip-irrigated olive orchard (cv. Koroneiki), Israel (EF).

Figure 10.3 Papaya flowers develop in the leaf axils. Some trees bear only female flowers, or bisexual flowers, while others only have male flowers. Some plants may have both male and female flowers – Swaziland (MKVC).

Figure 10.5 High-density papaya in Brazil (EF).

Figure 10.6 Drip-irrigated, high-density papaya plantation (four months old) in Linhares-ES, Brazil (LM).

Figure 10.8 Papaya (four months old). Close up of drip-irrigation lateral pipe and emitters, Linhares-EH, Brazil (LM).

Figure 10.9 Micro-sprinkler (foreground) irrigated papaya plantation (two years old), Linhares-ES, Brazil (LM).

Figure 11.5 Passion fruit growing in Kenya on a small farm with an innovative trellis system (MKVC).

Figure 12.4 Inflorescence emergence, called 'red heart', usually occurs 30 to 90 days after forcing. Each inflorescence contains 100–200 flowers – Swaziland (MKVC).

Figure 13.4 Pineapples interplanted with coconut (BGD), irrigated with micro-sprinklers – Petrolina-PE, Brazil (LM).

potential, relative soil water content and atmospheric demand. The measurements were made in a deficit irrigation experiment during an 'on year' (2006) in an orchard planted with large, 38-year-old trees (cv. Manzanillo de Sevilla, spaced 7 × 5 m = 285 trees ha^{-1}). The main conclusion from this detailed analysis was that the water needs of an orchard like the one described could be best assessed through the simultaneous use of the daily difference in the maximum trunk diameter of a stressed tree and a control well-watered tree, together with the corresponding difference in the daily water use (sap flow, L $tree^{-1}$ d^{-1}). Using other derivatives such as signal intensity offered no advantages. The number of instrumented trees still needed to be assessed.

Cuevas *et al.* (2012) extended the search for a suitable indicator to a high-density hedgerow olive orchard (1667 trees ha^{-1}; cv. Arbequina). Based on measurements made in a regulated deficit irrigation experiment with four-year-old trees with a heavy fruit load in south-west Spain (37° 15′ N 5° 48′ W), they concluded that the daily difference in water use was a better indicator of when to irrigate than the daily difference in maximum trunk diameter. This could either be used alone (although care was needed in interpreting the data), or in association with the daily difference in the maximum trunk diameter. The maximum daily shrinkage was not a reliable water stress indicator. The search goes on! But, since even relatively simple irrigation scheduling techniques are not being widely used by irrigators in commercial orchards, it can be questioned whether any of these sophisticated techniques is likely to be taken up in practice.

Osmotic regulation

Greece

Previously, Chartzoulakis *et al.* (2000) had demonstrated in a pot (volume 50 L) experiment lasting two years in Crete (Greece) the occurrence of osmotic regulation in severely stressed olive plants (cv. Koroneiki; pre-dawn leaf water potential down to –4.8 MPa). This was a result of solute accumulation (mainly mannitol and to a lesser extent glucose). There were also increases in the cell-wall elasticity and reductions in the volume of intercellular spaces. All of these attributes contributed to drought tolerance by maintaining cell turgor.

Tunisia

In a well-written paper, Ennajeh *et al.* (2008) reported the results of an experiment in southern Tunisia (33º 50′ N 10º 05′ E), in which the responses to drought of two contrasting cultivars, Meski and Chemlali, were compared. In a shaded, greenhouse study, the relative contributions to drought tolerance of osmotic adjustment and resistance to xylem cavitation (embolism) were assessed over a 60-day period. Several studies (cited by Ennajeh *et al.*, 2008) had shown that osmoregulation (by means of the synthesis and accumulation of solutes in cells) occurs in olive. By maintaining a positive pressure potential in the cell, the water potential gradient between the soil and the leaf is maintained, thereby facilitating water uptake from the soil. Another drought adaptation of olive trees is the capacity of the leaves to release about 60% of the water stored in their tissues at full turgor to transpiration.

The value of osmotic adjustment can, however, be negated during a drought by cavitation in the xylem vessels, which reduces the hydraulic conductivity of the xylem. Ennajeh *et al*. (2008) found that cv. Chemlali had a greater capacity than cv. Meski for osmotic adjustment and that both cultivars exhibited embolism. The xylem potential inducing a 50% loss of stem conductivity approached –7 MPa in cv. Meski, but was slightly less (more negative) than this in cv. Chemlali, suggesting that cv. Meski was more vulnerable to embolism than cv. Chemlali. In addition, cv. Meski maintained a slightly higher stomatal conductance and transpiration rate than cv. Chemlali throughout the period of severe drought. There was also a close (linear) relationship between pre-dawn leaf water potential and soil water potential (at a depth of 0.20 m) for both cultivars, with a small divergence from linearity for cv. Chemlali under very dry conditions. Although the differences were all small they confirmed the superior drought resistance of cv. Chemlali compared with cv. Meski, as previously reported by Ennajeh *et al*. (2006). Measurement of resistance to embolism may provide an effective way for screening cultivars suited to dry areas (Ennajeh *et al*., 2008).

Summary: plant–water relations

1. Olive trees conserve water under conditions of high evaporative demand by closing their stomata.
2. Stomatal conductances (generally) peak in the morning and then progressively decline during the remainder of the day.
3. Rates of photosynthesis and transpiration (and instantaneous transpiration efficiencies) follow a similar diurnal trend, except under conditions of high evaporative demand, when transpiration peaks later in the day than photosynthesis.
4. Mean daily stomatal conductances decline as the summer progresses.
5. In well-watered trees, rates of photosynthesis decline rapidly at temperatures greater than 28–30 °C, reaching zero at 40 °C.
6. In well-irrigated trees, pre-dawn leaf water potentials remain above –0.5 MPa, and at midday above –2.5 MPa.
7. Under dry conditions, midday stem water potentials can fall as low as –8 MPa, which is much lower than those experienced by most crop plants subjected to drought. The presence of fruit on a tree reduces the midday leaf water potential.
8. There is a positive linear relation between rates of sap flow and the saturation deficit of the air.
9. The hydraulic conductivity of a tree declines as the summer progresses, more so in rain-fed trees than in those that are irrigated.
10. There is no evidence that partial root-zone drying offers any advantages over regulated deficit irrigation in terms of tree water status.
11. There have been many attempts to develop ways of exploiting the sensitivity of trunk expansion to water availability as a means of scheduling irrigation. No clear consensus has yet emerged.

12. Maximum daily trunk shrinkage is correlated with maximum/midday daily temperature and maximum/midday daily saturation deficit.
13. Among all the tree indicators related to water status, the most promising for detecting water stress in an olive orchard are the *difference* in the maximum trunk diameter of a stressed tree and a control well-watered tree, and the corresponding *difference* in sap-flow rates, after calibration of the sensors, (both calculated on a daily basis).
14. Osmotic regulation (due to solute accumulation) and resistance to cavitation (due to narrow xylem vessels) contribute to the capacity of the olive to withstand drought. Cultivars differ in these attributes.

Crop water requirements

Since the pioneering work undertaken by Hendrickson and Veihmeyer (1949) in California, many attempts have been made to measure/estimate/model the actual water use of olive trees at different scales (see Fereres *et al*., 2011, for a succinct review). At the level of a leaf, measuring instantaneous transpiration is now an important component of fundamental studies of plant–water relations (as described above). Following its successful evaluation by Moreno *et al*. (1996) in Spain, the sap-flow approach has become widely used to estimate transpiration rates for individual olive trees. Alongside this approach, the micro-meteorological, aerodynamic method has been used, together with micro-lysimeters, in parallel studies to measure evapotranspiration (ET), together with its two principal components, evaporation (E) and transpiration (T), from a population of trees within an orchard. The aim of this research is to improve the precision of estimates of the potential water requirements (ET_c), by identifying appropriate crop coefficients that can be used for project planning and/or for day-to-day scheduling of irrigation in an individual orchard.

As Villalobos *et al*. (2000) and, more recently, Fereres *et al*. (2011) have highlighted, it is not appropriate, nor indeed possible, to specify a single value of the crop coefficient (K_c) for a widely spaced, evergreen tree crop like the olive. Its value varies among locations, and even between years, in response to changes in the saturation deficit of the air (due to the enhanced control of canopy conductance by the stomata) and evaporation from the soil surface. The complexity of the problem is exacerbated by the structural changes occurring in the industry. These are leading to a mosaic of olive orchards with, for example, differences in tree densities creating a wide range of crop cover.

In this section, two levels are considered: transpiration by a single tree and evapotranspiration by a plantation or an orchard. Since the contexts for the research at a national level will differ, selected examples of the results of research on these topics are again presented under headings for individual countries: Spain, Portugal, Morocco (all Mediterranean countries), Argentina and Australia (two relatively new producers).

Transpiration

Spain

In southern Spain (37.85° N 4.80° W; alt. 110 m), Villalobos *et al.* (2012), using large closed chambers in an olive orchard, monitored carbon exchange and transpiration of individual trees (cv. Arbequina, spaced 3.5 × 7 m = 408 trees ha^{-1}) during 2006 and 2007. Canopy conductance peaked in the early morning (0800–0900 h GMT) and then declined until sunset, in both the well-watered and the deficit-irrigated trees. By contrast, transpiration by the well-watered trees reached a maximum in early afternoon (1300–1400 h GMT) and declined from 1600 h onward. Daily transpiration rates equated to 0.6 to 3.4 mm d^{-1}. For deficit-irrigated trees, transpiration was virtually constant at a lower level (0.4 to 2.9 mm d^{-1}) from 0900 h to 1600 h. For comparison, ET_o varied between 1.1 and 7.1 mm d^{-1}. Net assimilation peaked early in the morning (0800–0900 h), before declining steeply from about 1500 h. Daily total assimilation varied from 10.8 to 21.3 g CO_2 d^{-1}. Instantaneous water-use efficiency, which was inversely related to the saturation deficit of the air (range 0 to 5.8 kPa), declined throughout the day, from about 30 g CO_2 L^{-1} at sunrise down to 4–7 g CO_2 L^{-1} at sunset.

Argentina

The olive industry is developing rapidly in Argentina, particularly in the arid areas in the north-west of the country. In the past 15–20 years, large (>100 ha) commercial olive orchards have become common (Rousseaux, 2008). By contrast to the Mediterranean region, there is no winter rainfall in this part of Argentina. During the summer, the total rainfall received is 100–400 mm. In Rioja province, irrigation is practised throughout the year with water obtained from subsurface aquifers 100–200 m below the surface. It is not known whether recharge of the aquifers is sufficient to replace the water being used for irrigation. Meanwhile, global climate change models predict a reduction in precipitation in this region (Rousseaux *et al.*, 2009).

This is the context in which Rousseau *et al.* (2009) began to investigate the leaf level responses of olive (cv. Manzanillo) to irrigation over a 40-day period in the winter (La Rioja province, 28º 33′ S 66º 49′ W; alt. 800 m). During this time period, there were only small reductions in transpiration rates and leaf conductances in the unirrigated trees compared with those that were well irrigated. Reference crop evapotranspiration rates (FAO, Penman) during the first four weeks averaged 2–3 mm d^{-1}, increasing to 4–5 mm d^{-1} towards the end of the experiment, when the soil profile to a depth of 0.90 m was close to permanent wilting point. Irrespective of the irrigation regime there was a strong curvilinear relationship between leaf conductance and the saturation deficit of the air, with conductance declining rapidly as the saturation deficit (recorded at midday) increased from 2 to 3 kPa, and declining less rapidly from 3–6 kPa. The stomata of both well-irrigated and dry trees behaved in identical ways.

Evapotranspiration

Spain

Recognising the need for a methodology that would allow reasonable estimates of K_c to be determined for a range of practical situations, Testi *et al.* (2006) developed a model for determining monthly K_c values that took into account four components: tree transpiration, direct evaporation of water intercepted by the crop canopy, evaporation from the soil surface and evaporation from the areas wetted by drip irrigation emitters. The model was validated against actual measurements of ET made over three years (1998–2000) in a young olive orchard (4 ha) in Cordoba, Spain, using both the eddy-correlation technique and the water-balance method (Testi *et al.*, 2004). The model was then used to simulate the water use (and its principal components) by an olive orchard at two sites, Cordoba and Fresno, in California, and for two hypothetical case studies, a traditional low-density (100 trees ha^{-1}) orchard converted to irrigation, and an intensive (300 trees ha^{-1}) modern orchard. The annual average values for K_c were 0.57 (low density) and 0.63 (high density), with monthly values for July (mid-summer) of 0.49 and 0.53. These are comparable with those values obtained by direct measurement in a young orchard (trees were from one to four years old): for a 'typical' summer day, without irrigation, $K_c = 0.15$, when the crop cover was about 5%, and 0.3 at 25% ground cover. When the wet soil surface patches associated with drip irrigation were taken into account, the corresponding values for K_c were 0.22 and 0.35, respectively (Testi *et al.* 2004). In the winter, when the soil surface was frequently wetted by rain, K_c sometimes reached 0.8.

In addition to the standard, representative weather data needed to calculate ET_o, to run the model it is necessary to know the tree density and canopy volume, the ground area wetted by the emitters and the frequency of irrigation/rainfall events. Using 20 years of daily data from Andalusia, Spain, the same researchers (Orgaz *et al.*, 2006) presented examples of the model's outputs for five different scenarios: a traditional olive orchard at immature and mature stages of development, a semi-intensive orchard (spacing 7 × 7 m = 204 trees ha^{-1}), also at two stages of development, and a modern, highly intensive orchard (spacing 7 × 3.5 m = 408 trees ha^{-1}). The range of values for the four components of the annual water requirements covering these five simulations were as follows: tree transpiration 156–708 mm (32–65% of total ET_c), soil surface evaporation 223–283 mm (25–53% of total ET_c), evaporation from wet soil 23–63 mm (5–7% of total ET_c) and intercepted rainfall evaporation 19–72 mm (4–10% of ET_c). For irrigation scheduling purposes the model could be used to predict water use by using long-term average weather data, adjusted as necessary at the end of the month.

Over a six-year period (2002–2007), the impact that the number of fruits on an olive tree (the crop load) have on its crop water status, crop water use and productivity was studied in south-west Spain (38° 51′ N 6° 40′ W; alt. 200 m) by Martin-Vertedor *et al.* (2011a, 2011b). There were two experiments, one with young trees and one with more mature, annually pruned trees (both cv. Morisca), in which deficit irrigation (including excess irrigation) was imposed (experiment 1: 75, 100 and 125% of ET_c; experiment 2: 60, 100 and 115% of ET_c). Crop loads were added as a variable, varied either artificially by thinning the fruit, or by comparing 'on years' and 'off years'. The following observations were made:

- The FAO method (Doorenbos and Pruitt, 1974), with crop coefficients (K_c) proposed by Pastor *et al.* (1998) and reduction coefficients (K_r) taken from Fereres *et al.* (1982), under-estimated crop water use (ET_c) in the control (100% replacement) treatment.
- A better estimate of ET_c was obtained by using the method proposed by Orgaz *et al.* (2006).
- Over the period from flowering to fruit colour change, ‘on year’ trees depleted more water from the soil profile (to a depth of nearly 1.0 m) than ‘off year’ trees.
- The absence of fruits reduced crop water use compared with medium and high crop loads, but canopy size was a much more important determinant of orchard water requirements than crop load.

Runoff and runon. As Castro *et al.* (2006) showed, rainfall redistribution in an orchard can be substantial because of localised runoff and runon induced by the spatial variability of the infiltration rate, rainfall interception by the trees and surface roughness. A physically based model, calibrated locally (Cordoba, southern Spain, average annual rainfall about 550 mm), predicted annual cumulative infiltration differences of between 40 and 100 mm between the area beneath the trees (olive) and the adjacent bare soil inter-row area. Such differences could represent fruit yields equivalent to 40 mm × 25 kg ha^{-1} mm^{-1} (= 1000 kg ha^{-1}) and 100 mm × 25 kg ha^{-1} mm^{-1} (= 2500 kg ha^{-1}) – see below. These yield gains are sufficiently large to justify developing rainwater runoff structures for rain-fed olive orchards.

Argentina

Following the previous work by Rousseaux *et al.* (2008), summarised above, the same team undertook a detailed study of the actual water use of drip-irrigated olives (cv. Manzanillo fina, spaced 4 × 8 m = 312 trees ha^{-1}; crop cover 23%) over a 12-month period with the aim of specifying appropriate values for the crop coefficient (K_c) for use in north-west Argentina (28° 33′ S 66° 49′ W; alt. 800 m) (Rousseaux *et al.*, 2009). Transpiration (T) was monitored using the sap-flow (heat-balance) method. Values obtained ranged from highs of 2.0 mm d^{-1} in mid-spring and summer to 0.23 mm d^{-1} in the winter. Direct evaporation from the soil surface (based on data from micro-lysimeters) varied between 0.2 and 0.6 mm d^{-1}, depending on the area of soil surface that was wetted and the frequency and duration of wetting. For a well-irrigated orchard, transpiration represented 0.45–0.60 × ET_o (except in the winter when values were close to 0.15), and evaporation from both the tree zone and the inter-row areas averaged about 0.20 × ET_o. These values were based on Penman–Monteith estimates of ET_o using weather data collected over bare soil (i.e. not grass). On average, transpiration represented about 70–80% of potential crop evapotranspiration (ET_c), except when the soil surface was kept exceptionally wet. Daily transpiration per unit of leaf area was linearly related to daily ET_o rates (range 2 to 10 mm d^{-1}; $r^2 = 0.84$) and to solar radiation (range 10 to 30 MJ m^{-2} d^{-1}; $r^2 = 0.80$), but exponentially related to average daily saturation deficits of the air (range 0.5 to 3.5 kPa; $R^2 = 0.85$). There was a suggestion that the relationship with daily mean temperature was two-stage linear, with no transpiration at temperatures below 13 °C, but linear from 13 to 30 °C ($r^2 = 0.93$). There was good agreement between estimated transpiration rates based on sap-flow measurements and values calculated from the model proposed by Orgaz *et al.* (2007).

Australia

In Australia, the olive industry has to compete with established irrigated crops such as grape vines for the scarce water resource. Prudent management of water is essential for a viable olive industry. This was the context in which the water use by four, carefully selected commercial olive orchards (groves) was monitored over two growing seasons (1999/2001) in South Australia (*c*. 34° S 140° E; alt. 300–500 m) (Nuberg and Yunusa, 2003). The trees were $>$10 years old and densities varied between 133 and 204 trees ha^{-1}. The soil textures varied between deep sandy, sandy loam over clay, clay loam over clay and clay loam over silty clay. Changes in soil water content (measured by using a neutron probe), from which ET was determined by using a simple water-balance equation, light interception (leaf-area index and ceptometer) and sap flow (heat-pulse sensors, on one site over one season only), were monitored. Transpiration (T) was estimated using an energy-balance, micro-meteorological approach, together with calculated values for stomatal conductances. The Priestley–Taylor equation was used to estimate evaporation from an open water surface (E_o) for the whole district, using local weather data. The validity of the sap-flow data was confirmed by a linear regression between sap flow and daily estimates of transpiration (T). In mid-summer, when daily average maximum temperatures and saturation deficits of the air reached 30 °C and 2 kPa, respectively, E_o peaked at close to 10 mm d^{-1}. Across the three irrigated orchards, total water use over a season (ET) was in the range 490–670 mm. By comparison on the rain-fed orchard, ET averaged only 316 mm. It was judged that not enough water was applied during midsummer by the irrigators to match potential transpiration rates and that the orchard had been under-irrigated by about 15%. The full water requirement was probably 900 mm at one orchard, where there was a permanent cover crop, and 700 mm at the two orchards where drip irrigation was used.

On average, where micro-sprinklers were used, transpiration represented $0.63 \times ET$, but $0.76 \times ET$ where drip irrigation was practised and there was less surface evaporation. Peak rates of transpiration reached 120–147 L tree^{-1} day^{-1}. Crop coefficients (K_c) based on the Priestley–Taylor estimate of E_o, averaged 0.38 on the irrigated estates and 0.23 on the rain-fed estate. (Note that in this case $K_c = ET/E_o$, not ET_c/ET_o as used elsewhere). Soil water extraction did not occur below 2 m depth. There was evidence that the stomata closed from midday onwards on hot, dry days. Estimates were provided of the monthly water requirements, and corresponding K_c values, for a drip-irrigated orchard at different stages of development (10, 20, 40 and 60% ground cover) (Nuberg and Yunusa, 2003). This was an interesting approach to obtaining useful information in situations where funds and facilities did not exist for conventional field experiments.

Morocco

In a semi-arid area region of Morocco (31.601° N 7.974° W), Er-Raki *et al.* (2010) evaluated the FAO-56 dual approach (Allen *et al.*, 1998) for estimating separately the soil evaporation and crop transpiration components of actual ET in a large (275 ha), flood-irrigated olive orchard (240-year-old trees, density 225 trees ha^{-1}). In a detailed comparison over two years (2003 and 2004), model simulations were compared with measured values of *ET* (eddy-correlation technique), and transpiration (scaled-up from sap-flow measurements). The agreement between the two approaches was considered to be good. The value so derived for the basal crop coefficient (K_{cb}, transpiration component only) was 0.54 × ET_o (where ET_o was calculated from the Penman–Monteith equation). Using this dual approach, Er-Raki *et al.* (2010) evaluated the irrigation scheduling practices used by one farmer on the project. This suggested that although twice as much water was being applied in a growing season (800 mm) than was needed (411 mm), the olive trees still experienced water stress during the summer, when evaporation rates were at their peak.

Portugal

In Portugal, the olive is traditionally a rain-fed crop and plays an important role in the rural economy. Existing orchards are now being irrigated and new ones created. The questions to be answered include how best to schedule irrigation in an orchard that for many years previously had been rain-fed only. This was the justification for a deficit irrigation experiment in southern Portugal described initially by Santos *et al.* (2007). Sap flow was measured at 30-minute intervals for four months in 2005 and for eight months from March to the end of August in 2006 in a low-density (12 × 12 m = 70 trees ha^{-1}), previously rain-fed, orchard planted with mature (cv. Cordovil, >80 years old) trees. The results for individual trees were scaled up in order to estimate transpiration from an equivalent orchard by monitoring the sapwood and canopy areas of randomly chosen trees and comparing these values with those of the sampled trees. In 2006, transpiration in the fully irrigated treatment totalled 700 mm, in the 60% sustained deficit replacement treatment the total was 750 mm, in the regulated deficit treatment the total was 650 mm and in the rainfall-only control the total was 400 mm. Rainfall over the eight months totalled 240 mm, the ET_o total was 1000 mm, whilst the depths of irrigation water applied were 880 mm, 450 mm and 70 mm, respectively (Ramos and Santos, 2009). In the well-irrigated trees the T/ET_o ratios declined over the summer months from 0.75–0.8 in March/April to 0.6 in June/July, before increasing to 0.9 in September. This reflected the effect of the high potential rates of evaporation ($ET_o = 7–8$ mm d^{-1}) experienced in mid-summer, which exceeded the capacity of the trees to transfer water from the wet soil to the sites of evaporation in the leaf at the rate needed (Santos *et al.* 2012). The implications of the results of this experiment in terms of yield are considered below.

Summary: crop water requirements

The principal source for each summary statement is given at the end of the sentence.

(a) Transpiration

1. For a well-watered crop, the canopy conductance is low early in the morning, reaches a peak at mid-morning and then progressively falls for the remainder of the day (Spain).

2. Because of strong coupling between the olive tree and the bulk atmosphere, the aerodynamic conductance is many times greater than the canopy conductance.
3. Transpiration reaches a maximum in the early afternoon and then declines from 1600 h onwards; net assimilation of CO_2 peaks early in the morning, and declines steeply from mid-afternoon onwards (Spain).
4. Instantaneous water-use efficiency declines throughout the day; it is inversely related to the saturation deficit of the air (Spain).
5. There is a close relationship (linear, Spain, Moriana *et al.*, 2002; curvilinear, Argentina) between leaf conductance and the saturation deficit of the air, irrespective of the irrigation regime.
6. After re-watering droughted trees, stomatal conductance and leaf water potential usually return to pre-drought levels within two days (Spain), but it has taken longer elsewhere (New Zealand). Sap-flow rates can take up to seven days.

(b) Evapotranspiration

7. It is not appropriate or indeed possible to specify a single value of the crop coefficient (K_c) for a widely spaced, evergreen tree crop like the olive.
8. When estimating ET it is necessary to take into account tree transpiration, direct evaporation of water intercepted by the leaf canopy, evaporation from the soil surface, and evaporation from the areas wetted by the drip or sprinkler systems.
9. The seasonal values of K_c to be used as a first approximation for the computation of ET for mature olive orchards with a crop cover of 50–60% in semi-arid areas with Mediterranean-type climates[2] and arid locations, are listed in Table 9.2 (Fereres *et al.*, 2011).
10. Trees with a heavy fruit crop deplete more water from the soil profile than low-yielding trees (Spain).
11. Because of localised runoff and runon, rainfall redistribution in an orchard can be substantial (Spain).
12. In a well-irrigated orchard, transpiration represents 0.70–0.80 × ET_c or 0.45–0.60 × ET_o (except in winter) (Argentina, Morocco).
13. The T/ETo ratio can change over the growing season (in the northern hemisphere) from as low as 0.4–0.5 (personal communication) up to 0.75–0.80 in March/April to 0.60 in June/July before increasing to 0.90 in September. This reflects the effect of high evaporative demand on stomatal conductance (Portugal and others).

Table 9.2 Values of K_c for olive orchards in semi-arid and arid locations (figures from Fereres *et al.*, 2011).

	Semi–arid	Arid
Spring	0.65–0.75	0.45–0.55
Summer	0.50–0.55	0.50–0.55
Autumn	0.60–0.70	0.55–0.65
Winter	0.65–0.75	0.40–0.55

14. Total water use (*ET*) over a season (depending on how this is defined) is in the range 490–750 mm; of which transpiration is 0.76 × *ET* with drip irrigation and 0.63 × *ET* with micro-sprinklers (Australia, Portugal).

Water productivity

Tree density, or the plant population density, is of critical importance when assessing productivity, and complicates attempts to compare the results of experiments across sites. Some of the issues are considered here.

The olive tree is transplanted early in the growing season (after up to two years in the nursery) at a density that is dependent on rainfall and on the pruning regime. This can be as little as 15–20 trees ha^{-1} under poor rain-fed conditions and in excess of 2500 trees ha^{-1} when irrigated. According to Pastor *et al.* (2008), the optimum (sustainable density) is probably about 400 trees ha^{-1} (7 × 3.5 m). Plant population studies for tree crops are not easy, but the results are fundamental to the success of a crop. They are particularly important in the case of the olive tree, where the planting densities cover such a wide range. How a crop responds to irrigation/drought and how we interpret the results of irrigation experiments are strongly influenced by the plant density.

For example, Guerfel *et al.* (2010) compared the responses of cv. Chemlali (planted in 1988) to four tree densities (51, 69, 100 and 156 trees ha^{-1}) over three years (2005–2007). The experiment was sited in a very dry area of Tunisia (35° 49′ N 10° 30′ E), where the average annual rainfall is only 250 mm. Because of weaknesses in the design of the experiment, the authors were unable to identify the optimum planting density for that location. This was partly because two of the three years that the experiment lasted were ‘off’ years in terms of yield. There are, however, three other lessons that can be learnt from this experience. First, with a long-term tree crop, three years is not long enough to monitor the cumulative effects of water-management treatments on crop productivity (especially a biennial-bearing crop like olive). Second, it is always wise to include in experiments of this type what may be regarded by others as crazy treatments. In this example, the spread of densities is very narrow (51–156). Why weren’t tree densities of 200, 500, 1000 or even 2000 trees ha^{-1}, for example, included in order to obtain a response curve, or better a series of response curves, depending on the rainfall in a particular year? We can learn more by extending the boundaries beyond what we recognise as being ‘normal’. Third, the optimum density will not only vary with the age of the trees, but also with the water regime (rainfall amount and distribution/irrigation): water therefore should also ideally be a variable, so that it is the water/density interaction that becomes the focus for the study, not density alone. In that way we may make progress.

When Salter and Goode (1967) reviewed the literature, virtually no research had been reported on the irrigation requirements of olive. It is only in the last 15–20 years that research has been undertaken. For example, of the ten irrigation experiments on olive in Spain cited in a review by Ruiz-Sanchez *et al.* (2010), all of the papers reporting the results had been published after 1996. Similarly, virtually all of the 17 papers reporting experiments on water productivity summarised below have been published since 2005. Here, they are again reported under the country in which the research was undertaken, in the following order: Spain, then Argentina, Australia, Israel, Italy, Morocco, New Zealand, Portugal, Tunisia and the USA.

Spain

In Spain, new irrigation developments are under close scrutiny because of chronic water shortages in many regions. If new water is to be allocated for the irrigation of olives, it is necessary to demonstrate the economic advantages of changing from rain-fed to irrigated cropping. To provide such evidence, Moriana *et al.* (2003), in an excellent paper, described the results of an experiment in Cordoba, Spain (38° N 4.8° W; alt. 110 m), in which various deficit irrigation regimes were compared with rainfall-only and fully irrigated control treatments. The experiment was conducted between 1996 and 1999 in a mature 18-year-old olive orchard (cv. Picual, spaced 6 × 6 m = 278 trees ha^{-1}) that had previously been rain-fed, but which was irrigated from 1995 onwards. The annual rainfall totals over the five years, beginning in 1995, were 478, 1095, 1043 and 468 mm, respectively. The soil was an alluvial sandy loam, over 2 m deep, with an available water capacity of 120 mm m^{-1}. The trees were irrigated (drip) on five days each week. Detailed supporting measurements were made of actual crop water use (*ET*; neutron probe), reference crop evapotranspiration (ET_o; Penman–Monteith equation; daily weather data), stem water potential (pressure bomb), trunk diameter variability (TDV; linear variable differential transformer) and abaxial leaf conductance (transient porometer), as well as fruit and oil yields. The following observations were made:

- Actual water use (*ET*) varied between <500 mm (rain-fed) to about 900 mm (well-irrigated).
- Depending on the year and the season, *ET* in the deficit treatments varied between 0.60 and 0.80 × ET_c for the well-irrigated treatment.
- Relative (to the well-irrigated control) maximum daily shrinkage of the trunk was a sensitive indicator of tree water status (for trees with a large fruit load).
- Stem water potentials at midday fell as low as–8 MPa in the rain-fed treatment, and to –7 MPa in the (regulated) deficit treatment (in which water was withheld during mid-summer, from 15 July to 15 September).
- By comparison, in the (sustained) deficit treatment, in which the same cumulative deficit was applied progressively over a season, the stem water potential never fell below –3.8 MPa.
- Virtually complete midday stomatal closure occurred during the summer/late summer in the rain-fed and regulated deficit treatments, respectively, especially in 1999.
- The maximum trunk diameter of well-irrigated trees with a low fruit load expanded more or less at a constant rate over a season, whilst the trunks of trees with a large fruit load grew at variable, but slow rates. Trunks of trees in the deficit treatments actually shrank slightly.

- As a result of the biennial yielding habit of olive, yields for two years were combined to develop curvilinear relationships between yields (t ha^{-1}) and *ET* (mm):

  For oil

  $$Y = -2.78 + 0.011ET - 0.006 \times 10^{-3}ET^2$$

  $$R^2 = 0.59, n = 23, P < 0.001$$

  For fruit

  $$Y = -16.84 + 0.063ET - 0.035 \times 10^{-3}ET^2$$

  $$R^2 = 0.71, n = 23, P < 0.001$$

Connor (2005) has re-plotted these data.

- Despite major differences in the levels of water stress experienced by trees in the two deficit irrigation treatments, there were no differences in yield between regulated (summer-concentrated) and sustained (progressive) stress. Both treatments were equally effective in reducing *ET* without a corresponding loss in yield.
- There was no evidence to support the idea of withholding irrigation in the alternate years when there is little or no fruit (an ‘off’ year), and concentrating the water in the productive year (an ‘on’ year).

Similarly, Iniesta *et al.* (2009) reported the results of a detailed, follow-up experiment at the same site in southern Spain. This time three treatments were compared, a control (fully irrigated) and two deficit treatments. These were: (1) sustained deficit irrigation: 25% of the quantity of water applied to the control was distributed proportionally throughout the irrigation season, (2) regulated deficit irrigation: the same total quantity of water was applied overall, but irrigation was withheld from July 1 to September 10–15 (midsummer). As in the experiment reported by Moriana *et al.* (2003), the trees (cv. Arbequina: spaced 7 × 3.5 m = 408 trees ha^{-1}) were irrigated (using drip irrigation) five days a week. The experiment continued for three years, 2004–2006. The principal findings were as follows:

- Midday leaf water potentials did not fall below –1.7, –2.9 and –3.6 MPa in the control, sustained deficit and regulated deficit treatments respectively. The amount of water applied to the control treatment was based on the product of ET_o (calculated from the Penman–Monteith equation) × K_c (a crop coefficient).
- In all three years, deficit irrigation reduced vegetative growth (shoot length, by up to 50%, and number of leaves); deficit irrigation also reduced the rate of increase in canopy volume.
- Although the rate of increase in fruit volume was reduced during the dry season in both deficit treatments, compensatory growth occurred after the autumn rains began or when irrigation was resumed.
- Fruit yields were greatest in the fully irrigated control treatment, and were about 25% less in the deficit treatments (the result in particular of fewer fruit following a reduction in the number of leaf pairs and associated flower initiation points).

- Oil yields from both deficit treatments were similar, being 13–20% below those of the control. This reduction was less than that for fruit yield. The oil concentration was higher in the fruits harvested from the deficit treatments than from the well-watered control.
- Annual evapotranspiration totals (*ET*) were reduced by 30–35% in the two deficit treatments (from *c*. 1000 mm, the control, to 600–700 mm, both deficit treatments). The corresponding transpiration totals (*T*) were 700 and 350–380 mm, a reduction of 45–50%.
- By comparison, intercepted solar radiation was reduced by only 18–20%, which implies that there was stomatal closure to conserve water.
- The amounts of oil produced per unit of intercepted solar radiation were similar for all treatments, averaging 0.16 g MJ^{-1}.
- For the control treatment, water productivity, based on the averages for two years (2004/05 and 2005/06), was 0.45–0.5 kg (olive oil) m^{-3} (irrigation water applied). The corresponding values for the two deficit treatments were about three times greater, at between 1.3 and 1.7 kg m^{-3}.
- When based on *ET*, water productivities, for 2005/6 only, were 0.24 kg (oil) m^{-3} (the control) and 0.30 kg m^{-3} (both deficit treatments), an increase of 25%.
- The corresponding values for transpiration alone were 0.34 (the control) and 0.55 kg (oil) m^{-3} (both deficit treatments), an increase of 62%.
- Alternate bearing and the initial variability in canopy volume and fruit load complicated a similar analysis of fruit yields. Deficit irrigation delayed fruit ripening.

In the two deficit irrigation experiments reported by Martín-Vertedor *et al*. (2011b), and described above, water stress reduced average yields of fruit in direct proportion to the reduction in transpiration:

$$Y = 1.23T - 21.2$$

where Y is the relative fruit yield (%; range 50–100%) and T is the relative transpiration (%; range 55–100%); $r^2 = 0.88$; $n = 8$. The cultivar used (Morisca) is considered to be particularly sensitive to water stress.

A linear relationship was also obtained between fruit yield (y) from individual ‘on trees’ (range 5–45 kg $tree^{-1}$) and the estimated annual transpiration (t) of each tree (range 200–500 mm):

$$y = 0.078t - 2.52$$

$$r^2 = 0.63; n \approx 50$$

A long-term (nine-year, 1998–2006) irrigation experiment in southern Spain (37.28° N 4.26° W) failed to show significant yield responses to irrigation (applied daily by drip) in individual years (Melgar *et al*., 2008). But when fruit yields (cv. Picual, spaced 7×7 m = 204 trees ha^{-1}) were aggregated over nine years, there was a significant 25% yield benefit over the rain-fed control treatment. This was equivalent to an average yield increase of about 10 kg $tree^{-1}$ each year. There was no additional benefit from applying 20% more water than the estimated soil (clay loam) water deficit indicated. ET_c was estimated using the Doorenbos and Pruitt (1974) method with appropriate values for K_c and K_r (based on the area of soil shaded by the canopy). There was little evidence of biennial bearing with cv. Picual. Since the yield benefits were small (the trees had a relatively small canopy), the authors did not consider irrigation to be justified in this location, where the average annual precipitation was 700 mm and ET_o was 1250 mm.

Argentina

In a follow-up experiment to that reported by Rousseaux *et al.* (2009), and described above, the growth and yield responses of six-year-old trees to five sustained deficit-irrigation treatments ($K_c = 0.50, 0.70, 0.85, 1.0$ and $1.15 \times ET_o$) were monitored by Correa-Tedesco *et al.* (2010) over two years, 2005–2007. The aim was to specify a locally derived value for the crop coefficient (K_c) that could be used to calculate ET_c. The experiment was conducted in the same commercial context, and on the same site in north-west Argentina, with the same cultivar (Manzanillo fina) planted at the same density (312 trees ha^{-1}), as described by Rousseaux *et al.* (2009).

Vegetative growth increased with the quantity of water applied (up to $K_c = 1.0$ to 1.15), whilst the yield of fresh fruit peaked with less water, $K_c = 0.7$ to 0.85. When K_c was below 0.7, fruit yields were reduced following a reduction in fruit number. Since excess vegetative growth can cause management problems in the orchard, it is preferable to avoid excessively large trees. These are difficult to harvest, and need to be pruned frequently. As a result of this research, the advice offered to growers in north-west Argentina by Correa-Tedesco *et al.* (2010) was to plan irrigation assuming a K_c value of 0.70 in the main growing season, September to May. In this way fruit yields would be maximised without creating excess vegetation. The water productivities (irrigation water applied) for fresh fruit obtained in the second year of the experiment ranged between 1.4 kg m^{-3} and 2.1 kg m^{-3}.

Australia

In their study of water use on four commercial olive orchards in South Australia, Nuberg and Yunusa (2003) calculated the water productivity (fresh fruit) of all four orchards. Yields varied considerably from site to site and from year to year (from 1600 kg ha^{-1} to 20 700 kg ha^{-1}). The corresponding water productivities varied accordingly, from 0.22 to 3.2 kg m^{-3}, based on ET, and from 0.36 to 4.9 kg m^{-3}, when based on transpiration (T). For individual trees, water productivities varied from 0.4 to 2.1 g L^{-1} (ET) and from 0.9 to 2.8 g L^{-1} (T).

Israel

On the coastal plain of Israel, the effects of the timing of water applications, relative to the stage of growth, on fruit and oil yields were evaluated in a four/five year study (Lavee *et al.*, 2007). There were nine treatments, the two extremes being full irrigation (537 mm applied), and rain-fed only (no irrigation). The other seven regulated-deficit treatments all had half the maximum amount of water applied (264 mm), but the timing varied during the season (from April 14 to December 15), according to the pre-determined schedule. When water was needed it was applied at weekly intervals by drip irrigation, the soil was a sandy loam, and the cultivar (Muhasan) was five years old at the start of the experiment, spaced at 4 × 7 m (= 357 trees ha^{-1}).

Irrigation increased the annual yield of fresh fruit, averaged over four years, which included two 'on years' and two 'off years', from 7.2 kg tree^{-1} (rainfed) to 39.2 kg tree^{-1} (fully irrigated). The yields from the deficit treatments were all similar at 25–26 kg tree^{-1}. The best of these was the one in which all the water was applied between mid-July (after pit (stone) hardening had ended) and mid-October (two weeks prior to harvest), which yielded 32 kg tree^{-1}. Full irrigation increased the individual mean fresh fruit mass from 1.8 to 5.1 g. The figures for oil yield were 1.1 (rain-fed), 4.4 (full irrigation), 3.7 (average of six deficit treatments) and 3.9 kg tree^{-1} (the best deficit treatment) The oil content figures were 15.1, 11.3, 13–14 and 12% of the fresh weight, respectively. Note that the reduction in oil concentration in the well-irrigated treatment was more than compensated for by the increase in fresh weight of the individual fruit. Irrigation delayed ripening (Lavee *et al*., 2007). These conclusions are very similar to those reached nearly 50 years earlier, also in Israel, by Samish and Spiegel (1961).

In summary, a 50% reduction in the amount of water applied only reduced fruit yield by 19% and oil yield by 13%. This implies that it is 'better' to plant twice the area of land and apply half the theoretical quantity of water needed to obtain maximum total yield than to irrigate fully a smaller area. The success or otherwise of this approach to improving water productivity in this or similar locations is dependent on the amount and timing of winter rainfall, and the water storage properties of the soil (Lavee *et al*., 2007).

Italy

In a brief paper, Sebastiani *et al*. (2012) summarised the results of a trial in southern Italy (41° 06′ N 14° 43′ E; alt. 250 m), in which deficit irrigation (drip) was applied over the period from the beginning of pit hardening (when the fruit had reached half its final size) to when it had achieved its final size and started to change colour (known as veraison). Yields of dry fruit over two seasons (2006 and 2007) increased with the increase in the depth of water applied, up to 100% replacement of ET_c. Yields from cv. Frantolo were greater than those from cv. Leccino at all four watering levels (rain-fed, 0.33, 0.66 and 1.0 × ET_c). Yield differences were due to larger individual fruits. The percentage oil content was similar at all watering levels. The main advantage of deficit irrigation scheduling was the improved control of vegetative growth without a corresponding reduction in fruit yield. Tognetti *et al*. (2006) had earlier reported similar results from experiments conducted in 2003 and 2004 with the same treatment combinations.

The long-term effects of deficit irrigation on vegetative growth, flowering and yield components of young olive trees grown in a high-density orchard for oil production were investigated by Caruso *et al*. (2013) at the University of Pisa (43° 01′ N 10° 36′ E). Different irrigation regimes were imposed from the fourth year after planting (in 2003) through the onset of fruit production (2006), until the trees had reached full production (2009). The trees (cv. Frantoio) were planted at a density of 513 trees ha^{-1}. All were uniformly irrigated (drip irrigation) from 2003 until 2006, when differential treatments were first imposed from July to October. The key observations over the course of this experiment were as follows:

- Water applications to the fully irrigated treatment were calculated as follows: $ET_c = K_c \times K_r \times ET_o$, where $K_c = 0.55$ and $K_r = 0.60$, 0.80, 0.90 and 1.00 in 2006, 2007, 2008 and 2009, respectively.
- Applying about 50% less water ($0.5 \times ET_c$) than was applied to the fully irrigated treatment ($1.0 \times ET_c$) reduced the yield of fresh fruit over the four years by about 32%, but the oil by only 18%. These relative values are similar to others cited by Caruso *et al.* (2013).
- The oil content declined at very high water stress levels, but not at low stress levels (pre-dawn leaf water potentials down to –5.2 MPa and at 50% depletion down to –2.8 MPa). Citing others, the researchers noted that the oil content of the fruit is also influenced by the number of fruits on the tree, a condition that seems to interact with the irrigation level.
- When yield per tree was expressed as the ratio of tree yield to the cross-sectional area of the trunk, the fully irrigated treatment and the 50% deficit treatments were judged to have similar yield efficiencies.
- Vegetative growth was reduced by about 10% in the 50% deficit treatment. No delay was observed in the onset of fruit production. Trees produced a full crop in 2006.
- The researchers concluded that, starting from the onset of fruiting, deficit irrigation is a sustainable practice that can be used for oil production. The effect on tree size is important for modern olive growing. Deficit irrigation for table olives is not recommended.

Morocco

In a companion paper to Centritto *et al.* (2005), the effects of partial root-zone drying on growth, yield and water productivity of olive trees (cv. Picholine marocaine) at the same arid site in southern Morocco were described by Wahbi *et al.* (2005). The experiments covered two years, one of which was an ‘off’ year (2002) and the other an ‘on’ year (2003). Yields of fresh fruit in both years were similar to those in the control drip-irrigated treatment ($1.0 \times ET_c$ replacement, where $ET_c = 0.7 \times ET_o$, derived from a USWB Class A pan), and in the treatment in which the same quantity of water ($1.0 \times ET_c$) was applied every two weeks, but on alternate sides of the tree. Both these treatments out-yielded the two other partial root-zone drying treatments. In these two other treatments, both of which also had similar yields, only half the quantity of water was applied ($0.5 \times ET_c$) either alternating every two weeks or every four weeks on each side of the tree. Average yields in year 1 in the control treatment were 35 kg tree^{-1}, compared with 27 kg tree^{-1} for 50% replacement, and in year 2 they were 90 kg tree^{-1} and 77 kg tree^{-1}, respectively. The total volumes of water applied (including 57 mm rain) over the growing seasons were 23 m^3 tree^{-1} year^{-1} ($1.0 \times ET_c$) and 11.5 m^3 tree^{-1} year^{-1} ($0.5 \times ET_c$). The corresponding water productivities as presented were 1.6 and 2.4 kg m^{-3} (year 1) and 4.0 and 6.7 kg m^{-3} (year 2). The yield advantage was mainly due to an increase in fruit number. There were no differences in the percentage oil content. Since there was no direct comparison with a regulated deficit irrigation treatment, it is not possible to judge the effectiveness of partial root-zone drying, as was the intention in this experiment.

Portugal

Ramos and Santos (2010) reported the results of another regulated deficit-irrigation experiment, this time with the emphasis on quantifying the likely commercial risk to farmers of converting low-density (<100 trees ha^{-1}), rain-fed, traditional (80+ years old) orchards to a higher tree density, irrigated orchard. The risk to the Alentejo region of southern Portugal (38° 05′ N 07° 17′ W; alt. 75 m) was perceived by the olive industry to be a reduction in quality leading to a loss of the 'protected designation of origin' seal of quality status within the European Union and the benefits that went with that attribute. In a comparison of four treatments (cv. Cordovil; 70 trees ha^{-1}) over two years (2006 and 2007), the sustained deficit treatment ($0.60 \times ET_c$) yielded about 50% more oil (year 1, 970 kg ha^{-1}; year 2, 200 kg ha^{-1}) than the fully irrigated treatment (650 and 120 kg ha^{-1}), despite receiving 49% less water. Biennial bearing is self-evident in these figures: it was even more pronounced in the two drier treatments. The corresponding water productivity values in 2006 and 2007 were: 0.22 and 0.04 kg (oil) m^{-3} (irrigation), and 0.07 and 0.01 kg m^{-3}, for the sustained deficit and fully irrigated treatments, respectively. There was no significant adverse effect of any of the three irrigation treatments, compared with the rain-fed control, on the numerous chemical and sensory characteristics of the oil, nor on its commercial value, which could still be classified as 'extra virgin'. The regulated deficit-irrigation treatment in which water was only applied before flowering, at the beginning of pit hardening and before crop harvesting, was less successful than expected. The timing of the irrigations in this treatment resulted in a net accumulation of leaves and fewer flowers in one year, which limited production in the following year (Ramos and Santos, 2010).

Ancillary measurements made during the course of the experiment showed that the pre-dawn leaf water potential fell just below –1.0 MPa in both the well-irrigated and in the sustained-deficit treatment. Midday values for both these treatments were in the range –2.35 to –2.85 MPa. A decline in stomatal conductance during the middle of the day, even when the soil was wet, was associated with large saturation deficits of the air. These sometimes reached 5.5 kPa.

Tunisia

The effect of irrigation on the quality of the olive fruit and its oil (cv. Arbequina) was evaluated in some detail by Dabbou *et al.* (2010) in north-western Tunisia (36° 18′ N 09° 07′ E; alt. 500 m), where the average annual rainfall is 450 mm. Three irrigation regimes were compared: 0.5, 0.75 and $1.0 \times ET_c$. The fresh weight of individual fruits was similar across the three treatments. In the case of the oil, the irrigation regime had little effect on free acidity or peroxide values. Irrigation increased the palmitic acid content, but reduced the content of oleic and linoleic acids. These are all fatty acids. Differences were observed in the content of phenolic compounds in the oil, but the concentration of alpha-tocopherol was unchanged. In general, irrigation had a positive effect on fresh fruit quality and oil content.

USA (California)

A deficit-irrigation experiment, with seven, drip-irrigated watering treatments (ranging from 0.15 to 1.40 × ET_c) was conducted over two seasons (2002 and 2003) in the Sacramento Valley (39° 30′ N 121° 34′ W; Grattan *et al.*, 2006). The plant density was very high (1700 trees ha^{-1}; cv. Arbequina). Fruit yields increased with the depth of irrigation water applied (range 50–600 mm) in a second-order relationship (R^2 = 0.79–0.99). By contrast, the oil content of the fruit (percentage fresh weight) declined linearly with the quantity of water applied. This meant that there was a broad plateau in the oil-yield response curve to water applied (from 200–500 mm; 0.40–0.90 × ET_c) for oil. All the irrigation treatments produced oil of very high quality.

In an advisory leaflet for growers in California, where olives are grown primarily for the table, Wheeler *et al.* (2008) interpreted the results of a regulated deficit irrigation experiment conducted over four years in the San Joaquin Valley (cv. Manzanillo; density 239 trees ha^{-1}) and reported by Goldhamer (1999). When grown for the table, individual fruit size is as important as yield. The recommendation was, if possible, to provide enough water to replace all the water lost by transpiration and evaporation (1.0 × ET_c, where $ET_c = 0.75 \times ET_o$).

There were no yield or financial benefits from applying extra water. If there was insufficient water (mild deficit) available for irrigation, the recommendation was to reduce the quantity of water applied by 50% through mid-summer (that is from mid-June to the end of July), a water saving of 13%. If the deficit was greater than this (moderate deficit), the duration of the 0.5 × ET_c deficit irrigation could be extended by four weeks from the beginning of June to mid-August, a saving of 21% (equivalent to about 200 mm water 'saved' each year). If the water shortage was even greater (severe deficit) the period of deficit irrigation (50%) could then be extended from mid-May to mid-September, but with even less water applied (only 25% of the full water requirement) between mid-June and mid-August (a 40% saving, or 400 mm). The severe deficit treatment resulted in a 10% reduction in yield, and a 25% reduction in the gross revenue, following a substantial reduction in fruit size. This made it uneconomic to produce table olives under these conditions in California. This is an example of the practical application of regulated deficit irrigation. It is assumed that when the crop cover reaches 50% potential evapotranspiration (1.0 × ET_c) is reached.

In contrast, growers of olives intended for oil who are short of water for irrigation are advised not to exceed a 30% reduction in the water applied (0.70 × ET_c). Applying less water than this may reduce oil yields to the point that production in California becomes uneconomic, although oil quality is maintained.

Summary: water productivity

1. Numerous experiments have been done to compare the effect of sustained deficit irrigation and regulated deficit irrigation with rainfall only and/or fully irrigated control treatments.

2. This is in response to the international need for evidence to justify using scarce water supplies to irrigate olives, traditionally a rain-fed crop.
3. A confounding factor in this work is the wide disparity in the tree densities (from <100 to >1000 trees ha^{-1}) represented.
4. No one appears to have looked systematically at the interaction between soil water availability and tree density in olive orchards.
5. Other complications include biennial bearing, and initial variability in tree size, canopy volume and fruit load. For comparative purposes, trees with similar properties need to be selected.
6. With deficit-irrigation experiments it is always necessary to specify the control (100% replacement of ET_c) treatment with precision, as this defines the benchmark against which other treatments are judged.
7. Deficit irrigation (when supply is less than ET_c) limits vegetative growth; this is particularly important for tree management (Spain, Argentina, Italy).
8. Deficit irrigation also slows the rate of fruit expansion. Fruit yields peak with less than full replacement of water (when $K_c = 0.7$–0.85). Compensatory fruit growth occurs when the rains begin or when irrigation is resumed. Fruit number is reduced when $K_c < 0.7$. (Argentina, Spain).
9. Oil yield is reduced less than fruit yield for a given irrigation deficit. The quantity of oil produced per unit of intercepted solar radiation is the same regardless of treatment (Spain).
10. There is no convincing evidence that the timing of regulated deficit irrigation is important; fruit yields are proportionate to the amount of water applied (Israel).
11. Similarly, there is no evidence (from one experiment only) that there are any benefits from partial root-zone drying (Morocco).
12. Fruit yields under sustained deficit irrigation are similar to those from regulated deficit irrigation (midsummer): deficit irrigation delays ripening, compared with full irrigation.
13. There is no evidence of an adverse effect of irrigation on oil quality (Portugal) and there can be a net benefit (Tunisia). Reduction in oil concentration in well-irrigated fruits is more than compensated for by increase in fresh weight (Spain. Israel, USA). Sometimes, the oil concentration does not change (Italy, Morocco).
14. Water productivities are summarised in Table 9.3. Curvilinear relations were developed between yields of both fresh fruit and oil (Y, t ha^{-1}) over two years and evapotranspiration (ET, mm) (Spain).

Water productivity: FAO reconciliation

In the FAO Irrigation Drainage Paper 33, Doorenbos and Kassam (1979) gave a value for the water productivity of fresh olives (30% water content) of 1.5–2.0 kg m^{-3}. The corresponding figures for oil were 0.03–0.05 kg m^{-3}. In the recent FAO Paper 66, the (relative) fruit yield response curve to (relative) ET developed in Spain by Moriana *et al.* (2003) was found, within the margins of error, to fit data for other cultivars and locations (Fereres, 2012). For relatively small applications of water (100–150 mm),

Table 9.3 Summary table showing range of yield (oil and fresh fruit) responses to water (kg ha^{-1} mm^{-1}) in terms of total depth of irrigation water applied (*I*), or the equivalent totals for evapotranspiration (*ET*) and transpiration (*T*).

	Well irrigated			Deficit irrigated		
	I	ET	T	I	ET	T
Oil						
Spain	4.5–5.0	2.4	3.4	13–17	3.0	5.5
Portugal	1.0–4.0				4–22	
FAO, 1979	3–5					
Fruit						
Spain	9–10				9–10	
Argentina	14–21					
Australia		2–32	4–49			
Morocco	16–24 (year 1)					
	40–67 (year 2)					
FAO, 1979	15–20					
		Up to 30				

the water productivity was about 3.0 kg m^{-3}, for example at replacements between 0.5 to 0.8 × ET_c, but the yield response then tapered off rapidly between 0.8 and 1.0 × ET_c.

Irrigation systems

The following topics are considered under this heading: irrigation water quality and salinity, irrigation strategies when water supplies are restricted, irrigation scheduling and irrigation methods. The emphasis is on new or novel approaches specific to olives.

Water quality

The olive tree is traditionally considered to be moderately tolerant of salinity (e.g. Maas and Hoffman, 1977; Ayers and Westcot, 1985), a view that has been largely confirmed by the results of a long-term (1998–2006) field experiment in Spain (37.28° N 4.26° W). This was designed to assess the effect of low-quality irrigation water on the growth and yield of the olive tree. Irrigation water with three levels of salt concentration (0.5, 5 or 10 dS m^{-1}, mixtures of sodium chloride and calcium chloride) was applied to mature olive trees (cv. Picual; spacing 7 × 7 m = 204 trees ha^{-1}) by daily drip irrigation during the summer months for nine years (Melgar *et al.*, 2009). In addition, there were two irrigation regimes, one in which the soil was maintained close to field capacity and another in which 20% extra water was applied (a leaching fraction) to wash out any salts from the soil.

Numerous growth parameters were monitored throughout that extended period, but no differences between treatments were identified. The only exception was that the oil content (on a fresh weight basis) increased (significantly) by two to three percentage points with the increase in salt content of the irrigation water in four of the nine years.

It was considered that in areas with similar rainfall amounts (long-term average *c*. 700 mm) and distribution (mainly during the winter, only *c*. 30 mm from June to September, inclusive) it is possible to use saline water (up to 10 dS m^{-1}) to irrigate olive trees. The wisdom of this advice is constrained by the view that the cultivar used in this experiment (cv. Picual) is relatively salt tolerant compared with the many other genotypes that are grown commercially (Melgar *et al*., 2009).

A great deal of research has been undertaken on the mechanisms of salt tolerance in olive, and why cultivars differ in their responses. Much of the work has been done on seedlings under controlled conditions (e.g. see Gucci and Tattini, 1997; Cimato *et al*., 2010), and its relevance to long-term field conditions is uncertain. A recent paper described the responses of two contrasting mature cultivars (Barnea, salt tolerant and Proline, salt sensitive) to the application of saline water (drip irrigation) over a period of 11 years. The tolerance of cv. Barnea to salinity was believed to be associated with the relatively large mass of fine roots that developed around the emitters (compared with cv. Proline). This enabled water uptake to occur under high evaporation rates despite the saline conditions (Rewald *et al*., 2011).

Another aspect of water quality as it affects olives involves its role in disease transmission. A recent study in southern Spain has confirmed that irrigation water plays a part in the dispersal of the Verticillum wilt disease of olive (Garcia-Cabello *et al*., 2012). This threatening disease (*Verticillium dahliae* Kleb) is particularly prevalent in the Guadalquivir Valley, where there are 1.5 million ha of olive orchards, of which about 240 000 ha are irrigated. Verticillium is a threat to the olive industry worldwide as a result of the conversion of rain-fed orchards to irrigation. The pathogen survives in the sediment and is distributed in soil and plant particles suspended in the irrigation water. It has been found in all the components of the irrigation-water distribution system, from the pumping station, through the main canal to the soil surrounding the emitters on a drip-irrigation lateral pipe. Other crops within the irrigation schemes (e.g. cotton) act as hosts to the disease.

Irrigation strategies

There are three ‘deficit-irrigation’ strategies that have been used successfully with olives (Fereres, 2012): first, ‘sustained deficit irrigation’, in which the planned deficit is spread evenly over the season; second, ‘regulated deficit irrigation’ when the deficit is concentrated in the summer months (e.g. from pit hardening to the end of the summer) and third, alternating short cycles of water stress and relief depending on the growth stage. As Fereres (2012) stated, and as this review confirms, there is no evidence of the superiority of one strategy over another, it all depends on local circumstances and the need to limit the amount of water used. Where the irrigation system is the limiting constraint, any one of these strategies could be implemented. For soils with low water availability, regulated deficit irrigation is likely to work better than sustained or continuous deficit irrigation. This is also probably the most appropriate strategy in years with well-distributed late summer rainfall, or when there is a shortage of water delivered to the farm. In general, and particularly in years with no summer or early autumn rainfall (as can often occur in southern Portugal, for example) the sustained deficit-irrigation regime may be the better option for scheduling irrigation (Ramos and Santos, 2009). A contributing factor to decision-making is the capacity of olive trees to extract substantial quantities of water early in the season, where there is winter rainfall, from inter-row areas away from the strips of land wetted by drip irrigation.

Irrigation scheduling

Fereres *et al.* (2011) expressed their surprise that olive-tree growers had not used the water-budget method more widely for irrigation scheduling despite its simplicity. One difficulty is in quantifying the volume of available water within the extensive root zone and, with that knowledge, specifying the allowable soil water deficit. This challenge is due in part to the spatial variability in soil physical properties, and in particular to the largely unknown depth and distribution of the effective roots of olive trees. Fereres *et al.* (2011) also made the point that the olive has the capacity to extract water from soils at water potentials below the generally accepted lower limit of available water (permanent wilting point). This could be significant in fine-textured soils, but not in sands. The allowable soil water deficit probably also varies with the stage of crop development, with the flowering and fruit-set stages being particularly sensitive to water stress.

Monitoring the changes in the maximum daily shrinkage of the trunk of a tree with a dendrometer has been proposed as a possible way of automating the irrigation scheduling of trees, including olive. For this method to work, baseline reference values for trees well supplied with water are a prerequisite so that the influence of other climatic variables can be taken into account. Moreno *et al.* (2006) undertook such an analysis over 104 summer days during 2005 in southern Spain. For mature well-irrigated trees (cv. Manzanillo), the maximum daily shrinkage was closely correlated with the reference crop evapotranspiration (ET_o) rates (range maximum daily shrinkage 0.2–0.9 mm d^{-1}, ET_o 3–9 mm d^{-1}; $r^2 = 0.55$, $n = c$. 90), with the saturation deficit of the air and temperature recorded at midday being the most important individual weather variables (range saturation deficit 1–6 kPa, $r^2 = 0.83$; temperature 24–38 °C, $r^2 = 0.79$).

In an interesting comparison of how sap-flow measurements and models of plant transpiration could be best used to schedule irrigation in four fruit crops, including olive, Fernández *et al.* (2008) concluded that the transpiration ratio method offered the best approach. This is defined as the ratio of the actual daily water use divided by the potential daily water use of similar plants under non-limiting soil water conditions. Actual water use could be measured using sap-flow techniques, whilst potential water use was best estimated using a modelling approach, provided that it could be simplified so that it became a realistic practical option in commercial orchards. They dismissed the use of the ‘sap-velocity profile’ method, proposed by Fernández *et al.* (2001) and Nadezhdina *et al.* (2007), as it was too insensitive to be a reliable indicator of when to irrigate.

In order to determine the potential for variations in stem diameter to be used for scheduling irrigation in commercial orchards, Fernández and Cuevas (2010) undertook a comprehensive review of the research literature. They urged caution for the following reasons: stem diameter variability is affected by many other factors other than water stress, including seasonal growth patterns, weather, crop load, and plant age and size, which all require expert interpretation; the relationship between stem diameter variability and stem water potential is not always straightforward; there is considerable plant-to-plant variation, which may not always be compensated for by sensitivity analysis. The installation and maintenance of the sensors must also be of the highest standards to avoid erroneous readings. Although the reliability of this method can be improved if it is combined with other plant stress indicators, such as sap flow in the case of olive, variation in stem diameter is not yet robust enough to be used as the primary indicator of when to irrigate a commercial orchard.

Irrigation methods

Given the scarcity of water in most olive-growing areas, and the variable tree densities that exist, the choice of irrigation method is limited to those methods that can apply water (and nutrients) uniformly, close to the tree with minimum waste. Both drip (trickle) and micro-sprinklers have the potential for precision irrigation, providing they are well managed. In nearly all the experiments reported in this paper, one of these two methods, usually drip, has been used with apparent success (Figure 9.7).

Practical issues associated with the planning and selection of irrigation systems suitable for olive orchards are well described in a report by the International Olive Council (IOC, 2007).

Figure 9.7 High-density, drip-irrigated olive orchard (cv. Koroneiki), Israel (EF). See also colour plates section.

Conclusions

After being grown as a subsistence crop for several thousand years in dry areas around the Mediterranean basin, the humble olive tree has suddenly become the centre of attention. This renewed interest is in response, in part, to the perceived health benefits of olive oil, which has increased demand and improved the profitability of the crop. As a result, the crop is now being promoted and grown in countries away from the Mediterranean, where the climate is different, in particular rainfall amount and distribution. This includes countries in the so-called ‘New World’, such as Argentina, Australia, California, Chile and New Zealand. These producers, as well as progressive growers in the traditional areas of production are prepared to review and revise the crop-husbandry practices normally associated with the crop. This has led to fundamental changes in field agronomy, including increases in tree densities, the introduction of irrigation and the development of novel ways of training the tree in order to facilitate mechanical pruning and harvesting. This intensification has all occurred in the last 20 years or so (out of the last 5000 years!). It has been supported by the contributions from international scientists who have not only evaluated the practical implications of these changes in traditional orchard management systems, but have also been able to obtain the resources needed to research the basic science, which is important for the longer-term future of the industry. Perhaps the most important driving force to innovation has been the introduction of mechanical harvesting.

Interest in the crop by scientists in recent years has resulted in a proliferation of publications. For example, of the 100+ publications reviewed in this chapter, about 70 (70%) have been published since 2004, and this is not a complete list. A common theme has been the priority given by researchers (and their paymasters) to finding ways of minimising the amount of irrigation water needed, given the scarcity of water in many of the regions where olives are grown. The concept of regulated deficit irrigation has been the subject of much research in several countries. Indeed it has become a fashion or ‘scientific bandwagon’, resulting in some unnecessary duplication of effort, and not just for olive trees. The quality control of some peer-reviewed journals has to be questioned. Even after all this work, it is not immediately clear from this review what is the best water-management practice for growers to adopt under specific conditions, although micro-irrigation allows the control, in time and space, that precision irrigation of this type requires. Perhaps the proliferation of papers has confused the situation more than it has been enlightened. This is not to underestimate the significant advances made in our understanding of water management in olive orchards in the last three decades.

The olive has many of the physiological attributes that allow plants to survive for many years and to remain productive in environments with low and variable rainfall. Some of these processes are understood, others less so. No doubt, low-input, low-output systems of production will continue alongside the intensive orchards, and the research priorities for each system will differ. For low-input systems the priorities will continue to be to identify cultivars, and orchard management practices, that are outstanding in terms of water productivity. As Connor (2005) stated, ‘strategic decisions are the selection of cultivar, tree density and canopy size, together with surface management

Figure 9.8 Traditional olive grove, grown from three stems per tree at a density of about 80–100 trees ha^{-1} in Jaen, Spain during flowering (EF).

Figure 9.9 Olive orchards in Portugal (MKVC)

as tilled soil or as cover crop of selected species'. Alongside these decisions are the tactical day-to-day adjustments needed on tree pruning and understorey management. These will depend on the rainfall amount and its distribution, especially after dry winters and during dry summers (Figures 9.8 and 9.9).

Perhaps high-density (hedgerow), irrigated olive orchards, formed to suit mechanical pruning and harvesting, are the future. To quote Connor *et al*. (2011) ‘the challenge is to optimise the structure of new olive orchards, modify existing suboptimal orchards, and to develop canopy management systems to maintain the optimal structure once it has been defined’. Water management research will play an essential role in this process as the industry continues to develop from its 5000-year-old historic roots.

Summary

The olive tree is native to the coastal areas of the eastern Mediterranean basin. It has been grown in the area surrounding the Mediterranean for several thousand years, mainly as a rain-fed crop. Although the crop is spreading to new regions with similar climates, the Mediterranean region continues to be the centre of production (and research). Beginning with descriptions of the stages of crop development, this chapter then reviews the results of research on the water relations and irrigation need of the olive.

A period of low temperatures is required to induce flowering. Flowers are born in the spring on inflorescences that develop from buds in the axils of leaves formed on wood produced the previous year. The olive tree is prone to biennial bearing. Little research is reported on the root system of the olive, but roots can extend to depths of >2 m.

The olive has many attributes that help to protect it against drought, including the morphology of the leaf, and the capacity to conserve water under conditions of high evaporative demand through stomatal closure, osmotic regulation and resistance to cavitation. Stomatal conductances peak in the morning and then progressively decline during the remainder of the day. Rates of photosynthesis and transpiration follow a similar diurnal trend, except when evaporation rates are high. Instantaneous water-use efficiencies are inversely related to the saturation deficit of the air, whilst sap-flow rates are positively correlated with the saturation deficit.

There is no evidence that partial root-zone drying offers any advantages in terms of plant water status over regulated deficit irrigation. Despite numerous attempts, no clear consensus has emerged on how best to exploit the sensitivity of trunk expansion to water availability in irrigation scheduling. Maximum daily trunk shrinkage is correlated with the maximum daily temperature and the saturation deficit of the air. Ways of quantifying potential evapotranspiration (ET_c), and its components, using values of the crop coefficient (K_c) appropriate for specific crop cover and soil surface water conditions, and for semi-arid and arid areas, have been described.

In a well-irrigated, mature orchard, transpiration (T) represents 0.70–0.80 times ET_c or 0.45–0.60 times ET_o (reference crop evapotranspiration) (except in the winter). Total water use over a season is in the range 490–750 mm, in part depending on the method of irrigation used and the length of the season.

In response to the international need to justify irrigating olives, numerous experiments have been undertaken to identify the minimum amount of water necessary. These have not always been well done or well reported. A confounding factor is the wide

range of tree densities and cultivars represented. Deficit irrigation reduces vegetative growth and fruit expansion. Oil yields are reduced less than fruit yields. There is no evidence of an adverse effect of irrigation on oil quality. Yields from sustained deficit irrigation differ little from those from regulated deficit irrigation, regardless of its timing. Water productivities are very variable and difficult to reconcile due in part to biennial bearing, tree-to-tree variability and differences in tree population densities. Irrigation water quality, salinity, the realisation that Verticillium wilt disease is being distributed in irrigation water, irrigation strategies when water supplies are restricted and methods of irrigation scheduling are all discussed.

As production methods for this historical crop are intensified (high-density hedgerows, irrigated and mechanised orchards), so will our need to understand the role that water plays in the production process become ever more critical, especially in areas of water scarcity, for the foreseeable future.

Endnotes

1 Experiments where water is applied below the maximum requirements.

2 Semi-arid areas are assumed to have about 500 mm or more rainfall mainly falling between the autumn and spring when it is relatively mild, followed by dry, hot summers; arid areas have less than 400 mm rain, again with dry, hot summers but with colder winters. The higher K_c values should be used in high/frequent rainfall areas (Fereres *et al.*, 2011)

10 Papaya

Introduction

Papaya (*Carica papaya* L.) has never been found in the wild, but is believed to have originated in tropical America, probably in southern Mexico and neighbouring Central America. Papaya was taken by the Spanish to the Philippines in the sixteenth century from where it was soon introduced to India. It has since spread to most tropical and subtropical countries between latitudes 32º N and 32º S, and up to an altitude of 1300 m near the equator (Purseglove, 1968; Muthukrishnan and Irulappan, 1990). The ripe fruits are eaten fresh, and used in the preparation of soft drinks, jams and other processed products. The immature fruit contains a milky latex, which is a source of papain, a proteolytic enzyme. Papain has many practical applications, for example it is used as a meat tenderiser, by the pharmaceutical, textile and tanning industries, and in medicine.

In 2010, there were an estimated 438 000 ha of papaya in the world with an annual production of 11 million tonnes of fresh fruit. The principal producers were India (4.7 million t from 112 000 ha), Brazil (1.9 million t; 34 000 ha), Nigeria (0.7 million t; 94 000 ha), Indonesia (0.7 million t; 8,100 ha), followed by Mexico with 0.6 million t from 14 000 ha (FAO, 2012).These data suggest average yields between only 0.7 t ha^{-1} (Nigeria) and up to 86 t ha^{-1} (Indonesia). The reliability of some of these estimates is questionable.

In recent years, the physiology and water relations of papaya have been well researched, particularly in Brazil and on the island of Guam (USA). This chapter begins with a description of the stages of crop development (including roots), followed by reviews of plant–water relations, water requirements and water productivity, and irrigation systems.

Campostrini and Glenn (2007) have reviewed the environmental physiology of papaya, concentrating in particular on photosynthesis, whilst a general description of papaya culture can be found in Morton (1987a) and, with a focus on South Africa, in DAFF (2009).

Crop development

Vegetative growth

Papaya is a short-lived (it is productive for up to three or four years) large herb (not strictly a tree), although its stature is not that of a typical herbaceous plant. The hollow stem grows rapidly up to 10 m in height. It is usually unbranched (Figure 10.1). The

Figure 10.1 A lone papaya plant growing amongst sugar cane. The hollow stem grows rapidly up to 10 m in height. It is usually un-branched – Swaziland (MKVC).

xylem vessels are concentrated near to the periphery of the stem. Leaves emerge from the upper part of the stem in a spiral on nearly horizontal petioles (Figure 10.2). The stem and the leaves contain latex, as well as the immature fruits (Purseglove, 1968; Morton, 1987a; Reis *et al.*, 2006). The plants are dioecious, although hermaphrodite forms occur. Papaya is usually propagated from seed so there are few true varieties. The Hawaiian Solo, Blue Solo and more recent types are fairly uniform and are closest to varietal status. Consequently, most papayas are types rather than varieties, so fruiting characteristics are better considered in groups. This variability within a population makes irrigation experiments particularly difficult (see below). The planting density is within the range 1000–3000 plants ha^{-1}

Papaya plants are vulnerable to wind damage, especially when the soil is wet and the plants are bearing a heavy load of fruit. The influence of wind on the growth processes is of particular interest. For example, the sensitivity of papaya seedlings to wind has been demonstrated in a series of experiments on the island of Guam in the western Pacific Ocean (13º 26′ N 144º 47′ E). Guam is exposed to trade winds throughout the year. Over a three-week period of exposure to a constant, one-direction wind at speeds ranging between 0 and 2.5 m s^{-1}, the rate of dry mass gain by the young plants (three to six weeks old) declined continuously with increase in wind speed (this relationship was best described by a negative quadratic function; $R^2 = 0.83$ and 0.93 for the types tested) from an average of 1900 mg plant^{-1} to 900 mg plant^{-1}.The effect of water stress was additive to that of wind, i.e. there was no interaction between the two variables tested (Marler and Clemente, 2006).

Previously, Clemente and Marler (2001) had shown how wind exposure reduced several measures of seedling growth, including plant height, and leaf and stem dry

Figure 10.2 Papaya leaves emerge from the upper part of the stem in a spiral on nearly horizontal petioles. Note the flowers – Swaziland (MKVC).

weight, but had no effect on root dry weight. Not all the genotypes tested responded to the same degree, indicating genetic variability within the species for tolerance to wind. Subsequently, Marler (2011) described how wind reduced stem and leaf expansion rates, but not root extension. Adaptive responses to directional wind exposure included asymmetric increases in stem diameter on the side exposed to the wind.

Close spacing of papaya plants results in tall plants with thin stems, making them more susceptible to wind damage than plants grown at a wider spacing. In the US Virgin Islands (18° N 65′ W), Zimmerman (2008) compared the responses of three papaya types to three plant densities, corresponding to 6000, 3000 and 2000 plants ha^{-1}. In order to obtain a marketable crop during the holiday season, the plants were established in the field in double rows in February during the dry season, using drip irrigation. After six months, plants grown at the highest density had fewer fruits (*c*. 25 plant^{-1}) than those planted at the other two densities, both of which had a similar number (*c*. 41 plant^{-1}). The fruits were also set closer to the soil surface. The three types, Maradol (compact), Tainung 5 and Yuen Nong 1 (both standard size), chosen because they set fruit early, responded to plant density in similar ways.

Flowering

After a juvenile period, flowers begin to develop in the leaf axils (Figure 10.2). Some plants bear only female flowers, or bisexual flowers, while others only have male flowers. Some plants may have both male and female flowers. Male flowers are

Figure 10.3 Papaya flowers develop in the leaf axils. Some trees bear only female flowers, or bisexual flowers, while others only have male flowers. Some plants may have both male and female flowers – Swaziland (MKVC). See also colour plates section.

clustered on long panicles. Seedlings usually begin flowering about two months after planting out in the field, although the length of the juvenile period depends in part on the type (Sansom, 2003). Flowering continues throughout the year as new leaves emerge (Figure 10.3).

Fruiting

Papaya begins to bear fruit within a year after planting, sustaining high yields for two years (up to 100 fruits per plant per year) before yields decline. The fruit is a large, bulbous, hollow berry. It takes from four to six months after flowering for fruits to mature. Fruits formed from female flowers are oblong to nearly spherical. Those formed from bisexual flowers are pear-shaped, cylindrical or grooved (Figure 10.4). Marketable

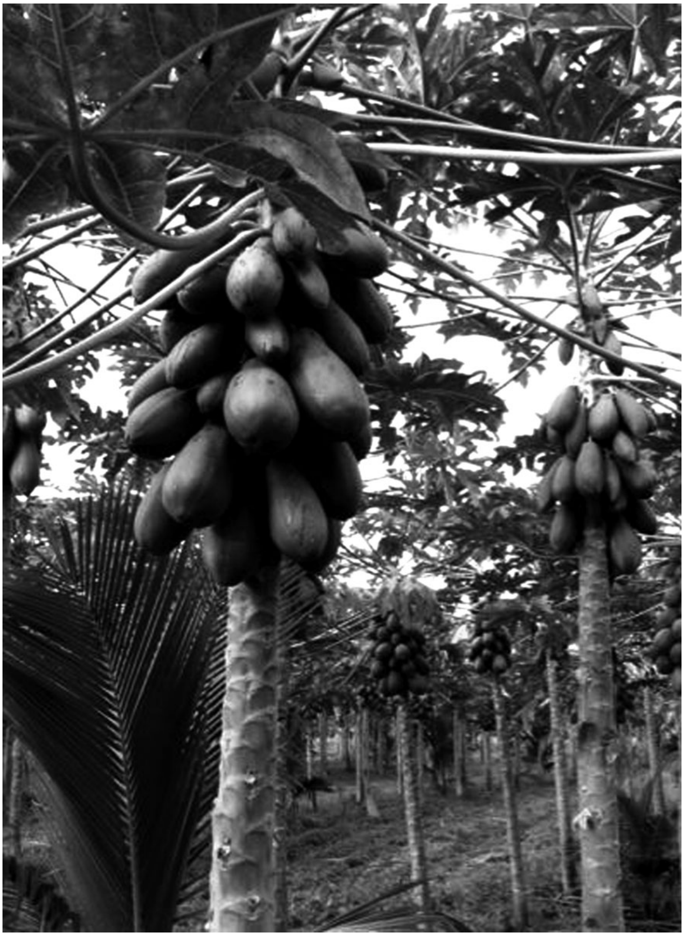

Figure 10.4 A papaya plant with fruit. Fruits formed from female flowers are oblong to nearly spherical. Those formed from bisexual flowers are pear-shaped, cylindrical or grooved – Brazil (EF).

fruits weigh from 0.3 to 3 kg, although small fruit are preferred for export. After three to four years, papaya plantations are usually uprooted and replanted, as yields decrease and the plants become too tall for economical harvesting. Fruit is harvested in most weeks, except during cool weather (Samson, 2003; DAFF, 2009; PIP, 2011a). When papaya plants are experiencing severe water stress, the leaf area declines, the fruits shrink in size and the new internodes for flowers are compressed.

In South Africa, the responses to temperature of clonal plants (Honey Gold) were compared in controlled-temperature greenhouses. A very hot regime (day/night temperatures 36/28 °C, respectively) led to rapid rates of development (9–10 leaves emerging each month), tall spindly plants, and small, early maturing fruits (170 days from flowering to ripening). In the coolest regime (20/12 °C) leaves emerged at half the rate (4–5 leaves month^{-1}), whilst fruits took 312 days to mature (Allan *et al*., 1987). The authors concluded that the optimum air temperatures for papaya growth and fruit production are in the range 25–30 ºC (day) and 11–16 ºC (night).

Roots

The root systems of young papaya plants were described by Marler and Discekici (1996a) at intervals of three and six months after being transplanted to the field in Guam. At the three-month stage the spread of roots covered an area of 3.5 m^2. After six months, this had increased threefold to 10.2 m^2. The corresponding total root lengths were 9.6 m and 975 m respectively, a tenfold increase.

In Bahia State, Brazil (12º 48′ S 39º 06′ W; alt. 225 m) Coelho *et al*. (2005) compared the root distribution of papaya (Sunrise Solo) irrigated by three different methods, namely micro-sprinklers and drip irrigation, either buried (at a depth of 0.25 m) or on the soil surface. The soil was a Latosol (sandy clay) and the average annual rainfall was 1143 mm. Root samples were collected from a grid of points on the wall of 0.75 m deep trenches, 19 months after planting in the field. By using a scanner, root length densities were calculated and lines plotted showing the distribution of lateral roots of similar densities. For surface drip irrigation, using a root length density of 0.04 cm cm^{-3} as the threshold value, 80% of roots were found within a depth of 0.25 m below the dripper, and within a width of 0.35 m. Although some roots were present at depths of 0.75 m, 80% (this is an arbitrary value chosen to represent the limits for an ‘effective’ root system) of the total root length was within 0.45 m of the soil surface. For the buried drip system, the greatest root density extended from the soil surface to a depth of 0.35 m and laterally over a width of about 0.55 m. Over 90% of the total root length was within a soil depth of 0.25 m. For the micro-sprinkler, the ‘effective’ root system occupied a larger volume of soil than it did for either drip system; the maximum root length density was at between 0.25 and 0.45 m depth with 80% of the total root length within 0.55 m depth. These data give a useful indication of where to site soil water sensors for irrigation scheduling purposes.

The results of a similar study, this time on Guam, were summarised by Marler and Discekici (1997a). During the dry season, roots proliferated under the drip irrigation lines in inverse proportion to the number of drip lines (1, 2 and 3). Where there was a single line, the density of roots, as recorded on the trench profile walls, was 3.7 times greater than in an unirrigated zone, 2.3 times greater where there were two lines, and 1.9 times greater where there were three lines. The authors concluded that papaya roots are highly morphoplastic, proliferating in wetted zones when only part of the root zone is irrigated. One dripper line per row was considered to be adequate.

In an unusual experiment on Guam, Marler and Discekici (1997b) investigated root distribution of papaya (Red Lady) growing on a steep slope (60–70%). Roots were exposed and mapped on the uphill and downhill faces of trenches excavated 7 and 17 weeks after planting. Afterwards they were separated from the soil and their length and dry mass determined. There was a greater concentration of lateral roots on the downhill side on both sampling dates (64 and 69% by mass, 56 and 71% by length, after 7 and 17 weeks, respectively). In addition, after 17 weeks, 34% of the roots on the uphill side were located above a horizontal plane positioned at the stem base. The authors considered that, when monitoring crop water use, these differences in root distribution justified installing soil water sensors both sides of a papaya plant growing on a steep slope.

Campostrini and Glenn (2007) stressed the importance of a papaya plant having a mycorrhizal network for improved water and nutrient uptake.

Summary: crop development

1. Papaya is a short-lived large herb, although its stature is not that of a typical herbaceous plant.
2. The plants are dioecious.
3. Papaya seedlings are sensitive to wind and mature plants are vulnerable to wind damage.
4. Flower buds develop in the leaf axils and flowering begins about two months after planting.
5. Papaya plants begin to bear fruit within a year after planting, sustaining high yields for two years before yields decline.
6. Leaf production, flowering and fruiting are continuous processes.
7. The optimum air temperatures for growth and fruit production are in the range 25–30 °C (day) and 11–16 °C (night).
8. Papaya roots can reach depths of at least 0.75 m, but the ‘effective’ root depth (80–90% of the total root length) varies with the irrigation method, e.g. 0.45 m (surface drip), 0.25 m (subsurface drip) or 0.55 m (micro-sprinkler).

Plant–water relations

In this section the role of the stomata in controlling gas exchange (particularly photosynthesis and transpiration) and the influence of the dryness of the air, light intensity and soil water availability on these processes are considered.

Stomata

Stomata are found only on the lower leaf surface of papaya at densities of about 400 stomata mm^{-2} (El-Sharkawy *et al.*, 1985). Stomatal conductance is sensitive to the saturation deficit of the air, declining by 47% when the saturation deficit increases from 1–1.5 kPa to 3.5–4.5 kPa. There is a similar reduction in the rate of photosynthesis. This value compares with an 85% reduction in conductance for cassava, a very sensitive plant, and 30% for maize, which is less sensitive (El-Sharkawy *et al.*, 1985).

The sensitivity of stomatal conductance in papaya (Formosa group) to the saturation deficit of the air was also demonstrated by Reis and Campostrini (2008) in field measurements taken in Brazil (21° 27′ S 41° 15′ W). On cloudless days in October, when the saturation deficit averaged 2.2 ± 0.7 kPa, the stomata were virtually closed throughout the day (despite irrigation with a centre pivot). By contrast, on cloudy days in January, during the rainy season, the stomata were wide open early in the day (0800 h), before partially closing during the morning. The stomatal conductance then remained relatively constant from midday through the afternoon. The average saturation deficit during the day was only 1.4 ± 0.7 kPa. On both occasions the air temperature averaged 29–30 ºC. Rates of photosynthesis followed the same trends as stomatal conductances.

Photosynthesis

Papaya has a C_3 photosynthetic pathway. According to Campostrini and Glenn (2007), citing others, photosynthesis rates in papaya approach zero at saturation deficits of 6–7 kPa, even when the plant is growing in a wet soil. The stomata of papaya also respond rapidly to changing light conditions.

On the island of Guam, stomatal conductance was observed to decline within 60 s of a reduction in irradiance (from 2000 μmol m^{-2} s^{-1} to 325 μmol m^{-2} s^{-1}). Recovery began within one minute of a return to full sunlight, reaching its original value after three minutes. Photosynthesis responded even more quickly, declining within 20 s of the reduction in light intensity, and recovering rapidly. This tracking response by the stomata is important in the lowland tropics, where there is intermittent cumulus cloud cover leading to rapid changes in photosynthetic photon flux density. During the period of low irradiance, instantaneous water-use efficiency increased. Mild water stress enhanced the rapidity of the light tracking response (Clemente and Marler, 1996).

On Guam, Marler and Mickelbart (1998) observed partial stomatal closure during the middle of the day in well-watered field-grown plants (Red Lady), but only when there was a clear sky. This was associated with air temperatures of 34 ºC and saturation deficits of the air peaking at 2.4 kPa. On overcast days, stomatal conductances remained high throughout the middle of the day. With drought-stressed plants, gas exchange remained low and relatively constant during daylight hours on both clear and overcast days. Instantaneous water-use efficiencies followed similar diurnal trends. Leaf chlorophyll fluorescent characteristics were not influenced by drought stress.

Again on Guam, Marler and Discekici (1996b) conducted an experiment in which the effect of partial irrigation of the root system of papaya, grown in containers, on stomatal conductance was evaluated. Initially the roots were trained to grow into four compartments and kept well watered until the plants were established. Water was then withheld from one, two or three of the quadrants. Restricting access to water in this way had no effect on midday stomatal conductance.

Compacted soil has been shown to reduce gas exchange in papaya (Caampostrini and Yamanishi, 2001). All four genotypes tested in Brazil (two from the Solo group and two from the Formosa group) responded in similar ways to root restriction with reduced photosynthetic rates and stomatal conductances, even when the soil was close to field capacity. Since conductance was reduced more than net photosynthesis, instantaneous water-use efficiencies were increased in the compacted areas, especially for one type (Sunrise Solo TJ).

Transpiration

After successful calibration, the Granier heat-dissipation method was used to measure sap flow in papaya plants growing in a commercial orchard in Brazil (21º 27′ S 41º 15′ W; alt. 12 m) (Reis *et al.*, 2006). Measurements were made over a period of four days in October and again in January. There was a positive, but nonlinear relationship between instantaneous transpiration rates measured by porometry, and xylem sap flow. This relationship was explained, in part, by the time lag early in the morning between water loss by transpiration and the resultant sap flow. This was because water was taken initially from that stored in leaves, petioles and small branches. The maximum sap-flow values recorded corresponded to 15.6 L d^{-1} m^{-2} (leaf area).

In a follow-up study by Ferraz *et al.* (2011) in Brazil (19º 12′ S 40º 06′ W), sap-flow measurements again showed a time lag in the morning due in part to the large water reserve in the trunk. It was only post-midday that there was a close relationship between sap flow and whole-plant transpiration rates, as measured in the field with gas-exchange chambers on five-month-old plants (cv. Golden). However, there was a good linear correlation between hourly transpiration rates and calculated reference crop evapotranspiration (ET_o, $r^2 = 0.89$, $n = 18$). The actual water use over four days of measurement equated to 2.46 L d^{-1} m^{-2} (leaf area) or 8.6 L d^{-1} $plant^{-1}$. The average instantaneous water-use efficiency was 154 g water lost for each gram of CO_2 assimilated.

The observation by Clemente and Marler (2001) on Guam that evapotranspiration during daylight hours was less from plants exposed to wind than from those that were sheltered is of particular interest because it records a situation that theory predicts, but which is contrary to common perceptions. In contrast, at night, wind exposure increased water loss (probably due to direct evaporation from the soil surface). Assimilation was reduced when plants were exposed to wind, but only on sunny days. Respiration rates increased regardless of sky conditions.

There is some evidence that types differ in their physiological responses to the environment. For example, in a comparison of five different genotypes in Brazil, one (Golden) was identified that, during the middle of the day, had stomatal conductances (and transpiration rates) higher than the other four. However, over the 12-week period of measurements, photosynthetic rates were similar for all five genotypes (Torres-Netto *et al.*, 2009). In a similar comparison of five types in South India, one (Co7) stood out from the others in many of the attributes measured in the field during the summer months, including gaseous exchange processes, cell membrane integrity and various chlorophyll indices. Instantaneous water-use efficiency was also higher in this type than with the others (Jayakumar *et al.*, 2007). Net photosynthesis increased linearly with air temperature over the range from 20 ºC up to 35º C for all five types, before declining rapidly. Similarly, net photosynthesis peaked at a photosynthetic photon flux density of about 1600 μmol m^{-2} s^{-1}.

By contrast, in a comparison between three transgenic lines (genetically modified to confer resistance to ringspot virus) at the University of the Philippines, transpiration rates and stomatal conductances were similar among transgenic lines, and between transgenic lines and the non-transgenic control treatment (Cruz *et al.*, 2009).

Papaya is reported to be sensitive to waterlogging (low oxygen availability) (Campostrini and Glenn, 2007, citing others). Papaya is classified as moderately sensitive to salinity, with a threshold level for the saturated soil extract of 3 dS m^{-1} (Maas, 1993).

Summary: plant–water relations

1. Stomata are found only on the lower leaf surface of papaya.
2. Stomatal conductance is sensitive to the saturation deficit of the air.
3. The stomata of papaya respond rapidly to changing light conditions.
4. Midday suppression of photosynthesis has been observed in papaya as a result of partial closure of the stomata (but only on clear days).
5. Net photosynthesis peaks at an air temperature of 35 ºC.
6. Intermittent spraying of the leaf canopy with water can prevent the stomata from closing.
7. Early in the morning, there is a time lag between water loss by transpiration and the resultant sap flow. This is because water is taken initially from storage in the stem.
8. There was a good linear correlation between hourly transpiration rates and calculated reference crop evapotranspiration (ET_o).
9. Evapotranspiration during daylight hours was less from papaya plants exposed to wind than from those that were sheltered.
10. There is some evidence that papaya types differ in their physiological responses to the environment.

Crop water requirements

The water requirements of papaya do not appear to have been studied in any detail. There is one report from Cuba (22º 46′ N 82º 37′ W; alt. 6 m), where papaya is one of the main irrigated fruit crops, by Chaterlan *et al.* (2010), which describes an attempt to derive crop coefficients (K_c) based on a statistical, modelling approach. The K_c values obtained were all in the range 0.90 to 1.10, almost regardless of the stage of crop growth, and the estimate for the allowable depletion of the total available soil water was a consistent 0.40. Although the authors claimed that the indicators of goodness of fit between the observed and estimated data were good, there must remain some doubt about the validity of these K_c values for papaya elsewhere in the world.

Despite the paucity of experimental data, irrigation recommendations are still made to growers. For example, in subtropical South Africa, Government advice (DAFF, 2009) on the amount of water to apply to papaya in each season (in L d^{-1} $plant^{-1}$, including rainfall) was as follows:

Establishment 6–13; first autumn 6–13; first winter 4–9; first spring 9–1;7 first summer 13–26; second autumn 9–17; second winter 6–13; second spring 13–26; second summer 17–34.

Figure 10.5 High-density papaya in Brazil (EF). See also colour plates section.

It is not known on what evidence this advice is based. The effects of differences in tree density and arrangement on crop water requirements have also not been reported (Figures 10.5 and 10.6).

Summary: crop water requirements

1. Ways of estimating the water requirements of papaya on an orchard scale have yet to be evaluated.
2. There are no reliable published values for the crop coefficient (K_c).
3. There have been two attempts to measure transpiration by individual plants (based on sap flow).

Figure 10.6 Drip-irrigated, high-density papaya plantation (four months old) in Linhares-ES, Brazil (LM). See also colour plates section.

Water productivity

Several papaya irrigation experiments have been reported, all of which were designed to identify the minimum depth of water needed (deficit irrigation) to obtain the highest water productivity. The research was undertaken in India, Puerto Rico, Brazil (two reports) and the Canary Islands.

Srinivas (1996) reported the results of one such experiment conducted in Bangalore, India (13º 58′ N; alt. 868 m) over three years (1990–1992) on a sandy loam soil. There were six watering treatments: 20, 40, 60, 80, 100 and 120% replenishment of evaporation from a USWB Class A evaporation pan. Irrigation was applied on a daily basis based on a simple water-balance calculation (evaporation minus 'effective' rainfall), except at weekends. The rainy season extended from May to November, and over the three years rainfall totalled 265, 1292 and 803 mm y^{-1}. Water was applied by drip irrigation, either on the surface or buried (at a depth of 250 mm). After the seedlings (cv. Coorg Honey Dew: spacing 2 × 2 m) were transplanted in September 1992, the crop was irrigated uniformly for 60 days before the treatments were imposed. The total yields of fresh fruit recorded over 28 months (36 months from planting) increased linearly with depth of water applied from 97 t ha^{-1} at 20% replacement to 121 t ha^{-1} at 60% replacement. At 80, 100 and 120% replacements yields were similar, averaging 130 t ha^{-1}.

The yield differences were the result of both an increase in the number of fruits (from 15 to 28 plant^{-1}) as well as individual fruit size (from 0.8 to 1.5 kg). It is difficult to interpret the water-use efficiencies cited in the paper ('water-use' is not clearly defined), but, when recalculated, the incremental values, in terms of yield response to irrigation water applied, are 17.9 (from 20 to 60% replacement) and 0.78 kg m$^{-3\ 1}$ (from 60 to 80% replacement).

The results of an irrigation experiment conducted in the semi-arid zone of the Caribbean island of Puerto Rico (17° 44′ N 66° 38′ W), where the 28-year mean annual rainfall total was 917 mm, have been reported by Goenagaa *et al.* (2004). The five irrigation treatments were again based on applying a fraction of the evaporation from a USWB class A pan, this time over a two-year period (1996–1998). The way in which the water requirements were calculated is complicated and open to question. For example, to determine potential evapotranspiration (ET_c), values were chosen for the pan coefficient ($K_p = 0.70$) and for a 'modified average crop coefficient' ($K_c = 0.42$). Thus:

$$ET_c = 0.42 \times 0.70 \times E_{pan}$$

The depth of water applied to each of the five treatments was then calculated, at weekly intervals, as a fixed proportion of ET_c, namely: 0.25, 0.5, 0.75, 1.0 and $1.25ET_c$. Treatment $1.0ET_c$ was considered to be the theoretical optimum. Allowance was made for rainfall. The papaya type was Red Lady (spaced 1.8 × 1.8 m; 3100 ha^{-1}), the soil was a Mollisol (fine loam), which was covered with a silver polythene mulch. Water (and fertiliser) was applied by trickle irrigation on alternate days. There was a linear response between both the number of harvested fruits and the total fresh weight of fruit and the value of the pan factor (a surrogate for the amount of water applied). This implies that even a pan factor of 1.25 did not equate to the optimum quantity of water. Marketable fruit (yield range from 50 to 78 t ha^{-1}) made up 78% of the total fruit number in both extreme treatments. There was no effect of treatment on the sweetness (Brix index) of the fruit. The water productivity, calculated from the data presented in the paper, equated to 2.8 kg (fresh marketable fruit) m^{-3} (irrigation water applied).

A similar type of experiment was undertaken in the Northern Fluminense Region of Brazil (21° 45′ S 41° 19′ W). This time there were seven water-replacement treatments, ranging from rainfall only (the control) to water applications (with micro-sprinklers) equivalent to 0.40, 0.80, 1.20, 1.60, 2.00 and 2.40 times the reference crop evapotranspiration (ET_o), where ET_o is the evaporation from a USWB Class A pan. Total yields of fresh fruit (Improved Sunrise Soil 72/12) obtained over a 16-month period increased with the depth of irrigation water applied from 7.4 t ha^{-1} (80 mm irrigation; total rainfall 1268 mm) to 53.0 t ha^{-1} at $1.60ET_o$ (1749 mm irrigation). Yields declined if more water than this was applied. When averaged over the first five treatments (rain only to $1.60ET_o$), the water productivity (for irrigation) was again 2.8 kg m^{-3} (Almeida *et al.*, 2003).

In the state of Espirito Santo, Brazil, a similar selection of watering treatments was imposed over a 14-month period (1996/98). There was a linear yield response over the range of water applications from 0.40 to 1.20 times E_{pan} (USWB Class A × pan coefficient). Irrigation amounts were supplementary to rainfall, which averaged 1249 mm y^{-1}. It is difficult to judge the validity of the data, as no points are shown on the graphs, only best-fit lines for each of the three irrigation intervals that were compared. The commercial fruit yield responses to the water applied were 0.96 (at two-day intervals), 1.62 (three-day intervals) and 2.9 (five-day intervals) kg m^{-3}. The largest yield obtained was 31 t ha^{-1}, with a total water application (rain plus irrigation) of 2730 mm. Yield increases were due to the combined effects of larger fruit and more fruit per plant (Da Silva *et al.*, 2001).

Another irrigation experiment of a similar format was undertaken on the island of Tenerife, Canary Islands (28º 14′ N 16º 50′ W) (Santana *et al.*, 2008). The four treatments were all based on applying a proportion (0.2, 0.5, 0.8 and 1.1) of E_{pan} (USWB Class A). Allowance was also made for the area of the ground shaded by a plant at midday. It is not stated how the timing of an irrigation was determined. Treatments began when the first flower had formed. The experiment was repeated three times between 2000 and 2006. Allowance was made for 'effective rainfall'. Actual rainfall totals during the duration of each experiment ranged between 182 mm (13 months duration) and 285 mm (12 months). The corresponding E_{pan} totals were 1824 mm and 1583 mm. The plants (a dwarf type known as Baixinho of Santa Amalia) were spaced 2.5 × 2.5 m (1600 ha^{-1}); the soil was clay loam. The depths of irrigation water applied (by trickle) in one experiment ranged from 173 mm to 948 mm. In all three experiments the treatment with the most water applied (1.1 E_{pan}) yielded the most. The yield (fresh fruit) response per unit of irrigation water applied plus effective rainfall was similar between treatments and between years, averaging about 1.1 kg m^{-3}. The highest yield achieved was 11.5 kg $plant^{-1}$. There was only one harvest per plant. The yield differences were due to greater numbers of fruits, not to their size.

Summary: water productivity

1. Only five irrigation experiments with papaya have been reported.
2. All five compared yield responses to a selection of irrigation treatments based on applying a fraction of ET_c that was calculated from USWB Class A evaporation pan data.
3. In all cases, different pan coefficients were chosen for calculating ET_c, making it difficult to compare results.
4. The experiments were of variable and limited duration – one, two or three seasons.
5. With one exception, there were linear responses between the yield of fresh fruit and the water applied, expressed as a fraction of ET_c.
6. Where the responses were linear, water productivity values were in the range 1.8 to 2.8 kg fresh fruit m^{-3} irrigation water applied.
7. Yield benefits were the result of increases in fruit size and sometimes also fruit number.

Irrigation systems

Little has been published on irrigation systems or scheduling methods that are specific to papaya. In the paper summarised above by Srinivas (1996), surface and subsurface trickle systems were compared at six different watering levels. Across all treatments, there was a significant +9% yield advantage in favour of subsurface irrigation (from 111 to 121 t ha^{-1}, totalled over the 36 months from planting) as a result of larger fruit (1.5 kg compared with 1.3 kg). Srinivas (1996) also commented on the need in India to replace surface (basin) irrigation of papaya with drip systems.

In Queensland, both under-tree micro-sprinklers and drip irrigation methods are recommended for papaya, but not overhead irrigation. The maximum water requirements for the two methods are given as 160 and 50 L plant^{-1} week^{-1}, respectively, whilst the conductivity of the irrigation water should not be above 1.2 dS m^{-1} (DAFF, 2012).

USAID (2008) published an interesting pamphlet on drip irrigation of papaya. Designed for the Ghana export horticultural industry, this well-illustrated training guide covers the installation, operation and maintenance of a 1 ha drip irrigation system for papaya. The design peak water requirement for plants more than seven months old is 5 mm d^{-1} or, for a plant population of 2000 ha^{-1}, 25 L plant^{-1} d^{-1}. This equates to five drip emitters per plant, each delivering 1 L h^{-1}, for five hours per day.

Irrigation scheduling

An irrigation experiment with papaya in south Florida was reported in great detail by Migliaccio *et al.* (2010), but it is difficult to see what, if anything, it contributed to our understanding of how best to irrigate this crop. A selection of different methods for scheduling irrigation was compared in two trials: three were soil-water suction-based, one was historic *ET*-based and one was a fixed time schedule. The conditions were unusual in that the plants were grown in raised beds, but with a maximum soil depth above bedrock of only 200–250 mm. Automated-switching tensiometers were used to control irrigation in the soil-based treatments. These often malfunctioned (power cuts, major leaks, equipment failure), whilst natural events (tropical storms and hurricanes) also contributed to the problems faced by the researchers in managing the experiments. Nevertheless the authors still felt it justified to list water productivities, as tonnes (fresh fruit) m^{-3} (water applied), to an ‘accuracy’ of three decimal places. It is difficult to understand how this paper came to be published in a refereed journal.

Summary: irrigation systems

1. Drip and micro-sprinklers are recommended for irrigating papaya (Figures 10.7, 10.8 and 10.9).

Figures 10.7 and 10.8 Papaya (four months old). Close up of drip-irrigation lateral pipe and emitters, Linhares-EH, Brazil (LM). See also colour plates section for Figure 10.8.

Figure 10.9 Micro-sprinkler (foreground) irrigated papaya plantation (two years old), Linhares-ES, Brazil (LM). See also colour plates section.

Conclusions

Although papaya is generally considered to be drought sensitive and responsive to irrigation, there is limited experimental evidence to support this view. Papaya is unusual amongst tree fruit crops in that it produces leaves, flowers and fruits on a continuous basis. Its productive life is also relatively short-lived. It should therefore be quite easy to establish cause and effect when developing relationships between water stress and yield. A uniformity of approach to irrigation experimentation and terminology would be a useful starting point. The sensitivity of the stomata to dry air is reasonably well established, but the actual water requirements have yet to be quantified with any precision. Unusually, a lot of effort has gone into explaining the effects of wind on the growth and development of papaya. Root systems are also well described. There is still a need to establish practical irrigation schedules for this remarkable crop.

Summary

Papaya has never been found in the wild, but is believed to have originated in tropical America from where it has spread throughout the tropics and subtropics. This fruit crop is particularly important in India and Brazil. Most research on the water relations of papaya has been undertaken in Brazil and on the island of Guam (USA). Papaya is a short-lived, large herb, growing to a height of up to 10 m. Leaves emerge from the upper part of the unbranched stem. After a juvenile period, lasting about two months, flowers begin to develop in the leaf axils. Flowering continues throughout the year as new leaves emerge. The plants, which are dioecious, begin to bear fruit within a year after planting, sustaining high yields for two years before yields decline. The 'effective' root depth varies with the method of irrigation, but can reach 0.55 m. The seedlings and the mature plants are susceptible to wind damage, a topic which has been well researched. Stomata are only found on the abaxial leaf surface. They are sensitive to changes in the saturation deficit of the air. Stomata also respond quickly to changing light conditions. On clear days, midday suppression of photosynthesis occurs as a result of partial closure of the stomata. In the morning, there is a time lag between water loss by transpiration and sap flow, as water is taken from storage in the hollow stem. Few attempts have been made to measure the actual water use of papaya, and there are no reliable published values for the crop coefficient (K_c). Limitations to the design of the papaya irrigation experiments reported so far make it difficult to reconcile the results in practical ways. Water productivities equivalent to 1.8 to 2.8 kg (fresh fruit) m^{-3} (irrigation water) have been obtained. Although papaya is generally considered to be drought sensitive and responsive to irrigation, there is a shortage of good experimental evidence to support this view. There is a need to establish practical irrigation schedules for this remarkable crop. A uniformity of approach to irrigation experimentation and a common, universally agreed nomenclature would facilitate this process.

11 Passion fruit

Introduction

There are two 'distinct' forms of passion fruit, the golden or sour passion fruit (*Passiflora edulis* f. *flavicarpa*) and the purple one (*P.edulis* f. *edulis*)[1]. Both are believed to have originated on the edges of the tropical rainforests in South America (Brazil). The golden form is grown in the lowland tropics, whilst the purple form, together with their hybrids, is found in the subtropics and at high altitudes (up to 3000 m) in the tropics. After the 'discovery' of the 'New World' in 1492, the first plant of the *Passiflora* group to be named outside South America was grown in Spain in 1553 (Bernacci *et al*., 2008). The passion fruit then spread rapidly and, by the end of the nineteenth century, it was widely distributed throughout the tropics and subtropics within the latitude range 0–35° N and S. Currently, about 95% of passion fruit production is with the golden or yellow form (Joy, 2010). In Australia, 95% of the planted area is with hybrid cultivars (Rigden, 2012a)

Reliable data on the current area and productivity of passion fruit are unavailable. von der Linden (2007) has indicated how four South American countries, Brazil, Ecuador, Colombia and Peru, dominate the world processed-pulp market. The structure of the industry varies from country to country. Brazil, for example, is both the largest producer and the largest consumer of fresh and processed passion fruit. It has been estimated by Joy (2010) (and others) that there are in total about 35 000 ha of passion fruit planted in Brazil, producing 480 000 t of fresh fruit, most of which is consumed within Brazil. With its numerous and extensive plantations, mainly in the provinces of Bahia and Sergipe, it accounts for 50–60% of the total world production (857 000 t of fresh fruit). According to Borges and Lima (2007) the passion fruit in Brazil is cultivated predominantly in small orchards 1–4 ha in area. Among fruit crops, it is an attractive farming choice, since it provides a fast economic return, with the income distributed reasonably evenly throughout the year (Bernacci *et al*., 2008) (Figure 11.1).

Ecuador is the world's largest exporter of processed passion fruit – puree, juice and concentrate. The juice is high in vitamin C (30 mg $(100\ \mathrm{g})^{-1}$). The fruit has been widely used in folk medicine in South America to treat a number of ailments, including anxiety (Zibadi and Watson, 2004). Thousands of Ecuadorian farmers and their families depend solely on passion fruit cultivation and fresh fruit sales; fruit is delivered to collection centres where it is sold on to processors. By contrast, in Colombia and Peru, processing companies either buy from contract farmers with no intermediaries involved or use fruit from their own orchards (von der Linden, 2007).

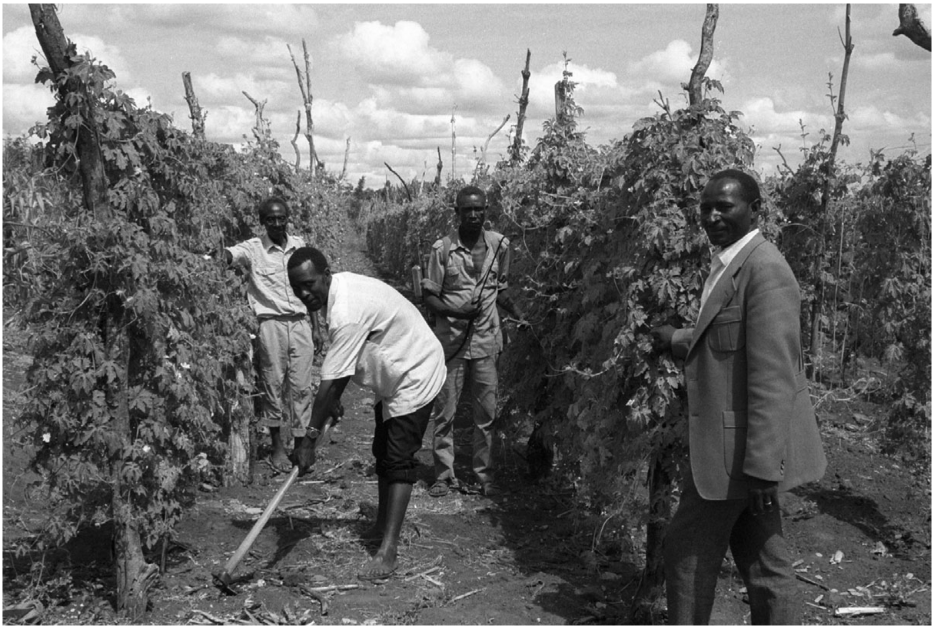

Figure 11.1 Weeding on a small-scale passion fruit farm. Amongst fruit crops, passion fruit is an attractive farming choice as it provides a fast economic return with the income spread fairly evenly over the year – Kenya (MKVC).

Menzel and Simpson (1994c) have reviewed the physiology of passion fruit. This followed an earlier review by Menzel *et al.* (1990). Morton (1987b) has provided a detailed description of the culture of passion fruit. Similarly, Borges and Lima (2007) have reviewed the (mainly) Portugese literature on the same topic. A detailed and comprehensive description of passion fruit, and its culture in India, can be found on the internet (KAU, 2013). In this chapter, an attempt is made to synthesise the limited amount of research reported on the water relations of passion fruit, and to do this in practically useful ways. It begins with a description of the stages of crop development in relation to water availability, followed by reviews of plant–water relations, water requirements and water productivity, and irrigation systems.

Crop development

The phenology of passion fruit is covered in the sequence: vegetative growth, flowering, fruiting and root growth. The visible symptoms of water stress are summarised.

Vegetative growth

Morton (1987b) described the passion fruit vine as a shallow-rooted, vigorous, woody perennial climber, climbing by means of tendrils. In commerce, the vines are supported

Figure 11.2 Passion fruit is a vigorous, perennial climber supported by a trellis upon which the vine is trained – Kenya (MKVC).

on wire trellises (Figure 11.2). Passion fruit vines are usually grown from seeds, but grafting onto yellow-form rootstocks is also practised. Planting densities are variable, typically 2.5 m or 3 × 3 m (1100–1300 plants ha^{-1}), but in warm areas plants may be thinned after the first year to give a density of 700 plants ha^{-1}. Leaves grow in a sigmoid pattern and, in a container experiment, an individual leaf reached a maximum area of 65 cm^2 when well-watered, over a period of 15–18 days (Turner *et al.*, 1996). Drying of the whole root system stopped leaf expansion after six days, but did not change the pattern of leaf expansion. Growth resumed after re-watering but the final size of the leaves was halved. A midday leaf water potential of –1.5 MPa was associated with a 50% reduction in the relative leaf expansion rate, whilst leaf production virtually ceased at leaf water potentials below –2.0 MPa. Leaf production is fastest at air temperatures in the range 24–38 °C (Menzel and Simpson, 1994b).

In detailed experiments, the root-zone temperature was varied over the range 10–38 °C for a grafted hybrid cultivar. The critical lower and upper root-zone temperatures for vine extension, leaf area, leaf node and leaf production were identified as 20 °C and 35 °C, respectively (Menzel *et al.*, 1994). Beyond these temperature limits the rates of growth were less than 90% of the maximum recorded. The corresponding temperatures for flower production were 20 °C and 30 °C, and for leaf and stem dry weight 18 °C and 34 °C, whilst maximum root dry weight occurred at 38 °C. The authors considered that productivity of passion fruit would be adversely affected in cool subtropical areas if the soil temperature at depths of 0.15 m was either below 20 °C or above 30 °C in the tropics.

Flowering

A single flower bud is borne at each leaf node on new growth (Figure 11.3). Cross pollination is mainly by bees. Flower (golden) receptivity (for pollen) declines sharply after about 1400 h (Souza *et al.*, 2004). Rain within two hours of pollination prevents fruit set (Morton, 1987b). Pollen is ripe three to four hours before the stigmas are receptive. Most golden cultivars are self-incompatible, and need to be cross pollinated. This is not the case with purple forms or hybrids. After a certain number of fruit (from 4 to 10) have set along a branch, a temporary cessation of new vegetative growth, flowering and fruit setting occurs. These processes do not commence again until the fruit is mature (Menzel *et al.*, 1990). Flower buds are not initiated under dry conditions. Pruning once a year stimulates new growth, whilst regular watering keeps the vine flowering almost continuously. Pruning is not practised in Australia because of its expense. Instead, growers re-plant an orchard when the vegetation becomes too dense, as this can lead to pest and disease problems (Rigden, 2012a).

Menzel *et al.* (1986) showed, in a glasshouse experiment in Australia, how even mild water stress (soil water potential of –0.01 MPa) can reduce all aspects of vegetative growth of a hybrid passion fruit, including the number of leaf nodes. The number of flower buds and flowers was also reduced. Flower bud initiation is the most sensitive stage of development, whilst developing flower buds appear to acquire some resistance to desiccation. Moisture stress also reduced flower size, but did not lead to premature abscission (Menzel *et al.*, 1986). Staveley and Wolstenholme (1990), in a very similar experiment in South Africa (with purple passion fruit grafted on to *P. caerulea* (red rootstock)), came to many of the same conclusions. In addition, the number of days to

Figure 11.3 Passion fruit flower. Heavy rain at flowering can prevent fertilisation – Sri Lanka (HDT).

first fruit set was reduced by soil water stress. Based on these observations, it was recommended that the soil water potential should be maintained above –0.02 MPa during the critical periods of flower differentiation and fruit set.

Fruiting

Plants start to bear fruit within six to eight months from field planting (Figure 11.4). The fruit matures 60–90 days from fruit set (Menzel *et al.*, 1990). Harvesting occurs throughout the year, but yields vary month by month. For example, in Brazil, during a so-called normal year, peaks of production occur in October and November (spring) and again in April (autumn). Crop distribution is similar in Ecuador, but with a subsidiary peak in July/August. In Peru, there is one large peak from July to September (representing 50% of the annual crop) and a secondary peak between January and March (30%).

Figure 11.4 Plants start to bear fruit within six to eight months from field planting – Uganda (HDT).

In Colombia, the main harvesting season is in June and July, and also January (von der Linden, 2007). In Queensland, yield peaks occur from May to August and from December to February (Passionfruit Australia Inc., 2012). Fruit set on one branch is harvested over a two- to three-month period. The centre of the fruit is filled with a pulpy aril that surrounds numerous small black seeds. Each plant can produce 300–600 fruits per year. Although, for example, a fresh fruit yield of 60 t ha^{-1} is possible in Kenya, a good commercial yield is 20–30 t ha^{-1} (Samson, 2003).

Roots

Although passion fruit is described as shallow rooted by Morton (1987b), there is little published evidence to support this view. According to KAU (2013), passion fruit has a superficial root system with 60% of the roots (by mass?) located within 0.30 m of the surface. According to Rigden (personal communication, 2012) roots extend to depths >1 m in some soil types (e.g. Aflisols) in Australia, but in most soils, roots are concentrated within 0.5 m of the surface. Root depth is limited in the field if plant roots are distorted when they reach the bottom of the nursery polybag. Most growers in Australia re-plant every two years, some every year, mainly to control pest, viral and fungal disease problems. This will limit the maximum rooting depth.

In two container experiments conducted in Australia, root growth was measured. In one experiment, although water stress reduced the absolute dry weight of roots, the proportion of plant dry matter translocated to the roots compared with the leaves and stems increased (Menzel *et al.*, 1986). In the second experiment, in which the soil volume available for the roots to exploit was varied, shoot weight was correlated with root weight, but a smaller proportion of dry matter was allocated to roots as the root weight increased (Menzel *et al.*, 1994). In a recent detailed review of 65 pot experiments (with different plant species), Poorter *et al.* (2012) showed clearly that pot size matters, and how important it was for researchers to identify the right size of pot to ensure that the results were not distorted by the influence of pot size on biomass production.

Visible symptoms of water stress

Menzel *et al.* (1986) observed the following changes in appearance after the imposition of water stress on pot-grown passion fruit hybrids. Stavely and Wolstenholme (1990) also recorded similar symptoms:

- Stems thinner
- Tendrils shorter
- Leaves and flowers smaller
- Side shoots fewer
- Young leaves become yellow-green
- Mature leaves become dull grey-green
- Basal leaves turn yellow and senesce prematurely

- Newly developed axillary shoots die
- Marginal and tip necrosis develop in the leaves
- Terminal shoots, young leaves and tendrils wilt at midday
- Guttation from glands on the leaf margins and from the floral bracts are reduced.

It is important to note that dry matter production is restricted long before these visible symptoms appear. Similarly, it should be remembered that symptoms of water stress develop much more quickly/suddenly in pot-grown plants than in similar plants growing in the field; there is also less time for the plants to adapt to the dry conditions.

Summary: plant development

1. Leaf production virtually ceases at a leaf water potential of –2.0 MPa, and expansion of new leaves is considerably reduced at –1.5 MPa.
2. A single flower bud forms at each leaf node of new growth.
3. Water stress reduces leaf and floral bud initiation.
4. Flower bud development and fruit set are less sensitive to water stress than leaf initiation.
5. Heavy rain at flowering prevents fertilisation; the pollen grains on the stigma burst on contact with water. Extended periods of rain result in poor fruit set.
6. Unevenness in crop distribution during the year may be linked to water stress and temperature variation.
7. There is little quantitative evidence to support the view that the passion fruit plant is shallow rooted.

Plant–water relations

Apart from a series of pot experiments undertaken in Australia, very little research appears to have been reported on the water relations of passion fruit. Turner *et al.* (1996) demonstrated how, by drying half the root system, non-hydraulic root signals influenced leaf expansion rates and flowering of passion fruit. Leaf expansion was reduced by 26% compared with a well-watered control, and water use was reduced by 21–27%. By contrast, there was no effect on the leaf water potential or on net photosynthesis rates. Plants with half the root system dry flowered five to seven days earlier than well-watered plants, but had the same number of open flowers one month after treatments ended. These results question the validity of scheduling irrigation on the basis of measurements of leaf water potential. In another pot experiment, Menzel *et al.* (1986) found that there were only small changes in leaf conductance in passion fruit over a wide range of leaf water potentials (–0.5 to –2.6 MPa).

In Brazil, Gomes *et al.* (2012) compared the responses to dry conditions and subsequent recovery of two container-grown passion fruit cultivars (Yellow Master (FB200) and Maguary (FB300)) in terms of chlorophyll-*a* fluorescent transients (F_v/F_m and ABS/RC ratios). Using the JIP-test, this evaluation showed that the two, one-year-old cultivars differed in the plasticity of their responses to drought and re-watering. FB200 plants had an advantage over FB300 plants in terms of their efficiency in utilising energy.

Summary: plant–water relations

1. A limited amount of research has been reported on the water relations of passion fruit. Most experiments published have used container-grown plants.
2. Some evidence suggests that partial root-zone drying can influence leaf expansion and time of flowering, independent of any direct hydraulic mechanism.

Crop water requirements

Advisory leaflets and other publications from Brazil indicate that the passion fruit does best where the annual rainfall is between 800 and 1700 mm, with mean air temperatures of 23–25 ºC (cited by Borges and Lima, 2007). In São Paulo State, Brazil (22º 43′ S 47º 38′ W: alt. 576 m), Silva *et al.* (2007) successfully used the Bowen ratio, energy-balance method to monitor the water use of passion fruit (cv. IAC 275). In this subtropical humid location, with a dry winter, two row orientations were compared, north–south and east–west. The plants, spaced 4 × 4 m, were supported on a vertical structure with a single wire 2 m above the ground surface. The crop was well irrigated. Measurements began about two months after transplanting. Over the 12-month (2003/04) period of measurement, the average potential evapotranspiration rates (ET_c) for both row orientations were statistically similar: namely, 4.1 mm d^{-1} (equivalent to 1500 mm y^{-1}), and 3.5 mm d^{-1} (1300 mm y^{-1}) for north–south and east–west orientations, respectively. In five individual months (December, January and February, and July and August) ET_c was greater in the north–south rows than the east–west. Peak rates of water use occurred in November (average 5.5 mm d^{-1}) and December (5.8 mm d^{-1}), both for the north–south row orientation, and the minimum rate of use was in July (2.0 mm d^{1}), in the east–west orientation. Unfortunately, no attempt was made to relate these ET_c figures to estimates of reference crop evapotranspiration (ET_o) in order to derive values for the crop coefficient (K_c).

In a lysimeter-based experiment with the yellow passion fruit in tropical Brazil (6° 53′ S 36° 02′ W; alt. 470 m), ET_c rates during apical vegetative growth after transplanting averaged 2.8 mm d^{-1}. They increased to 5.0 mm d^{-1} when the side branches were developing, and then to 5.7 mm d^{-1} when the plants were flowering and fruiting. When averaged across a number of ancillary treatments, the corresponding K_c values (based on a Penman–Monteith estimate of ET_o) were *c.* 0.57, 0.90 and 1.10, respectively. Irrigating with saline water (4.5 dS m^{-1}) reduced ET_c rates by 18% during vegetative growth and by 8% when the plants were in flower and forming fruit. An organic mulch reduced total water use (ET_c) by about 5% (Freire *et al.*, 2011). In a similar lysimeter study, again in Brazil, the values of K_c varied from 0.42 to 1.12 (Silva and Klar, 2002).

De Souza *et al.* (2009) used the water-balance approach to estimate the potential evapotranspiration (ET_c) of passion fruit in the Curu Valley in Brazil (3° 45′ S 39° 15′ W) over a ten-month period (2004/05), together with the corresponding K_c values. Basing their measurements on a 0.6-m deep soil profile, ET_c totalled 1500 mm in the 296 days (5.8 mm d^{-1}) following transplanting. The K_c values for the same three crop growth stages as defined above were 0.65, 1.13 and 1.25 (overall average value = 1.09), when based on ET_o (Penman–Monteith), or 0.7, 0.9 and 1.1 (mean = 0.9) for a USWB Class A pan.

Summary: crop water requirements

1. Evapotranspiration rates (ET_c) up to 5.8 mm d^{-1} have been consistently measured in Brazil, using three different methods: Bowen ratio, lysimeters and a soil-water balance.
2. The crop coefficient (K_c), based on a Penman–Monteith estimate of ET_o, varies with the stage of growth from about 0.6 during apical extension growth up to 1.10–1.25 in the reproductive phase.
3. The FAO Irrigation and Drainage Paper 56 does not mention passion fruit (Allen *et al.*, 1998).

Water productivity

Water stress (unquantified) reduces the current crop and also the development of flowering shoots for the next crop. Cropping is less seasonal with irrigation. A few controlled-irrigation experiments have attempted to quantify these responses, mainly in Brazil.

In Brazil (22° 43′ S 47° 38′ W), de Sousa *et al.* (2003) studied the yield response of golden passion fruit to irrigation (and potassium). The four (drip) irrigation treatments were based on applying a fixed proportion (in theory, 0.25, 0.5, 0.75 and 1.0) of the potential water use (ET_c) of a passion fruit plant, as recorded in a drainage lysimeter (measuring 1.5 m deep × 1.23 m^2 surface area). Supplementary watering was necessary from April to October, when the reference crop evapotranspiration rate (ET_o) varied between 1.8 mm d^{-1} and 4.4 mm d^{-1}. The actual volume of water applied in a year ranged from 927 L $plant^{-1}$ to 2706 L $plant^{-1}$, a threefold difference. As the vines were spaced 3.5 × 4.0 m apart (714 plants ha^{-1}), 2706 L $plant^{-1}$ equates to about 200 mm $year^{-1}$. The (commercial) yield response to water appeared to vary with the level of potassium fertiliser applied; at least the fitted response curves as published had different shapes. But, when averaged (crudely) over all five potassium treatments the yields from the two extreme irrigation treatments ($0.25 \times ET_c$ and $1.0 \times ET_c$) were almost identical.

In what appears to be the same experiment, de Sousa *et al.* (2005) later reported the water-use efficiencies (water productivities) for each treatment combination. Values ranged from 8 kg (commercial fruit) ha^{-1} L^{-1}, in the wettest treatment, up to 34 kg ha^{-1} L^{-1}, in the least wet treatment. It does not appear to be possible to draw any practically useful conclusions from this experiment. Carvalho *et al.* (1999) had earlier reported the results of a similar, 18-month duration experiment (with the yellow form) with variable amounts of water applied (six levels, from rainfall only up to 1.25 × ET_o), in combination with potassium fertiliser at four rates from 76 up to 760 g (K^+) plant^{-1} (as KCl). The highest yields of fruit were obtained from the 0.85 × ET_o treatment combination (namely, 0.85 ET_o with 434 g K^+ plant^{-1}).

Carvalho *et al.* (2000) reported on a similar experiment, again in Brazil, but this time with nitrogen and water as the two variables studied. There were six irrigation treatments: rainfall only (control), together with the replacement of fixed proportions of reference crop evapotranspiration (ET_o), namely from 0.25 to 1.25 × ET_o. Because only graphs showing statistical relationships without any data points are presented, it is not possible to judge the quality of the results and the validity of the conclusions.

In equatorial Kenya (alt. 2185 m) passion fruit is an attractive crop for small-scale farmers because it has good local and export markets, and can be harvested throughout the year (Figure 11.5). Guturuku and Isutsa (2011) reported the results of an irrigation experiment in Kenya with purple passion fruit vines grown in a silt-clay soil under a rain shelter. Water was applied at fixed weekly rates (2.5, 5, 10 and 20 L plant^{-1}) for a period ending 56 weeks after planting. It is not explained why or how these rates were selected. At a spacing of 1.5 × 1.5 m, 20 L plant^{-1} equates to only about 1.2 mm d^{-1}. After 56 weeks there was no difference in the cumulative number of fruits harvested between treatments (range, dry to wet, 200–228 fruit plant^{-1}), but there were differences in the

Figure 11.5 Passion fruit growing in Kenya on a small farm with an innovative trellis system (MKVC). See also colour plates section.

fresh weight of fruit (range 5050–6016 g plant^{-1}). There was no effect of mulch (black plastic, wheat straw, bare soil) on the cumulative number or weight of fruit. Neither the irrigation treatments nor the mulches had any effect on the many attributes of fruit quality recorded. Given the small quantities of water applied, and the failure to interpret the data in ways that might be useful, it is not obvious what can be learnt from this experiment.

Over a three-year period (2005–2007), Srinivas *et al.* (2010) conducted a field (drip) irrigation experiment in Bangladore, India (13º 58′ N; alt. 858 m). The two watering treatments compared were 25% and 50% replacement of evaporation from a USWB Class A pan, applied on a daily basis after allowing for rainfall. Seedlings (cv. Kaveri), 40 days old, were planted in the field at a spacing of 3 × 3 m, and subsequently trained on to a bower. The first harvest was made 185 days after planting, and harvesting continued for another 175 days, at intervals of eight to ten days. After the first 20 harvests, a total of 361 fruits plant^{-1} had been harvested from the 50% replacement treatment, compared with 305 fruits plant^{-1} from the 25% replacement (a reduction of 15%). The corresponding yields of fresh fruit were 23 and 19 kg plant^{-1} (–17%). In the second group of harvests (15 in total) fruit yields totalled 12 and 10 kg plant^{-1}, respectively (–19%). Yield differences were mainly the result of differences in fruit number, not size. The yield figures are averaged over four fertiliser treatments. As there was no control – ‘dry’ – treatment, nor a well-irrigated treatment from which to set yield limits, no broad conclusions can be drawn from this experiment. The (re-calculated) incremental water productivity, between the 50% and 25% replacement treatments (assuming that the term water-use means irrigation water applied), equated to 25 kg (fresh fruit) ha^{-1} mm^{-1} (irrigation).

Fruit cracking can occur during fruit development when heavy rain follows a period of dry weather. The fruit skin cracks because of abrupt changes in the water pressure (turgor) potential in the skin of the fruit, and the sudden expansion of the fruit that follows. As the fruit grows, the cracks become corky. Irrigation can help to reduce the incidence of fruit cracking.

Summary: water productivity

1. A few worthwhile irrigation experiments with passion fruit have been reported.
2. There is a need to undertake realistic field-based research to quantify the yield responses of passion fruit to water.
3. The only (crude) estimate of (irrigation) water productivity for passion fruit is 25 kg (fresh fruit) ha^{-1} mm^{-1}.
4. The crop is not included in the FAO Irrigation and Drainage Paper 66 (Steduto *et al.*, 2012).

Irrigation systems

In Australia, an Enviroscan was used to monitor the irrigation of passion fruit with micro-sprinklers (Anon, 2010). At the commencement of measurements there was full trellis cover with a good fruit load. Probes were located along the plant line, and sensors were placed at depths of 0.1, 0.2, 0.3, 0.5 and 0.7 m. Over the spring and summer, and the early autumn period (2009/2010), crop water use ranged from 2.5 to 5.4 mm d^{-1}, but declined to $<$ 1 mm d^{-1} in winter. In the sandy loam soil, the effective rooting depth was at least 0.7 m. The wetted diameter was 1.8 m, and the distribution uniformity from the micro-sprinklers was judged to be very good (>90%). The resultant Enviroscan graphs illustrating changes in soil water content over time at each depth, as well as daily totals of rainfall and irrigation, were informative.

In Queensland, Australia, irrigation is considered to be essential for growing high-quality passion fruit. Growers are strongly encouraged to schedule irrigation scientifically. Soil-water monitoring devices such as tensiometers and gypsum blocks, as well as capacitance probes, are recommended (Rigden, 2012).

In Brazil (6° 50′ S 38° 19′ W; alt. 235 m), Soares *et al*. (2008) compared the responses of yellow passion fruit to supplementary irrigation with saline water at five levels of electrical conductivity, ranging from 0.2 to 5.0 dS m^{-1}. Over a period of 10 months, there were no discernible adverse effects on any of the growth attributes measured, including yield. By contrast, Freire *et al*. (2011) found that irrigating with water with an electrical conductivity of 4.5 dS m^{-1} for 150 d after transplanting reduced growth and water use compared with the control treatment (0.5 dS m^{-1}).

Summary: irrigation systems

1. As with most fruit crops, micro-sprinklers and drip are the most effective and precise ways of irrigating passion fruit (combined with fertigation).
2. Beware damaging the pollen during peak flowering with sprinkler irrigation, alternatively irrigate at night.
3. The Enviroscan is a useful way of monitoring soil water content.
4. There is a limited amount of information on the response of passion fruit to saline irrigation water.

Conclusions

In Australia, by 2010, there were about 300 000 vines planted, producing in excess of 3000 t of fruit annually. The industry is looking to expand, and in 2010 published a Strategic Action Plan (Passionfruit Australia Inc., 2012). Some of the issues in that plan are highlighted here, since they are relevant to this chapter:

- Potentially, climate change and variability may impact the growing conditions in established production regions, leading to changes in productivity and business viability.
- Changes in available water for crop production, climate patterns and micro-climates that affect crop set and/or fruit quality, pest and disease pressures and a range of other factors have the potential to have a positive or negative impact on production.

- Optimal production capacity can be achieved through improved varieties, access to disease-free planting material and improved agronomic practices, including pest and disease, nutrition, canopy and irrigation management.

This review has highlighted at an international level the need to strengthen our scientific understanding of how passion fruit responds to its environment, in particular the role of water in its development and productivity. As an under-resourced, minority crop, the way forward for the passion fruit industry must be through international cooperation on research topics of generic importance, including water.

Summary

It is generally accepted that the two forms of *Passiflora edulis*, the golden and the purple, originated on the edges of tropical rainforests in Brazil. Extensive hybridisation has since taken place between these two forms and their hybrids. The passion fruit (a vine) is now grown throughout the tropics and subtropics. A limited amount of basic, fundamental research has been published on the water relations of passion fruit. Leaf production and expansion are both sensitive to water deficits, whilst water stress reduces leaf and floral bud initiation. A single axillary flower bud forms at each leaf node of new growth along with a tendril. Flower bud development and fruit set are less sensitive to water stress than leaf initiation. Heavy rain during pollination prevents fertilisation. Unevenness in crop distribution during the year is possibly linked to water stress and temperature variation. Potential evapotranspiration rates (ET_c) in Brazil varied between 3.5 and 5.8 mm d^{-1}. The value for the crop coefficient (K_c) increases from about 0.6 during apical vegetative growth up to about 1.25 during flowering and fruiting. Water productivities still need to be determined. Micro-sprinklers and drip are the most effective ways of applying irrigation water with precision to passion fruit. Opportunities exist for international cooperation in research projects of mutual interest on passion fruit water relations.

Endnote

1 Bernacci *et al*. (2008) have recently challenged the conventional view.

12 Pineapple

Introduction

A wild ancestor (*Ananas comosus* var. *ananassoides*) of the present-day cultivated pineapple (*Ananas comosus* var. *comosus*) is believed to have originated in South America (probably in the Paraná–Paraguay river drainage area, which straddles the equator). The domesticated pineapple has been traded and adopted as an important fruit crop on a continental scale for more than 3000 years (Duval *et al.*, 2003; Clement *et al.*, 2010). After the 'discovery' of the New World in the late fifteenth century, pineapple spread rapidly throughout the tropics.

Pineapple is grown at low elevations at latitudes between 30º N (Assam, India) and 34º S (South Africa) (Purseglove, 1972; Malézieux *et al.*, 2003). Pineapple-based production systems range from wild plants grown under tree cover, to intercropping systems that include pineapple and a wide variety of tree and herbaceous crops, to highly intensive monoculture (Malézieux *et al.*, 2003). In 2008, the main areas of pineapple production were Brazil (2.49 million t from 60 000 ha), Thailand (2.28 million t; 90 000 ha), the Philippines (2.21 million t; 58 000 ha) and Costa Rica (1.67 million t; 33 000 ha), the world's largest producer for the fresh market. Important producers in sub-Saharan Africa are Nigeria and Kenya. In Thailand, pineapple is predominantly a smallholder crop (95% of all producers are small farmers with holdings of 1–5 ha), whilst, by contrast, in the Philippines and Indonesia large plantations predominate (>20 000 ha each) (Figures 12.1 and 12.2). Pineapple is mainly grown for its fresh fruit, which is eaten as a dessert, or exported fresh or as a canned product. Pineapple is also used as an ingredient in a wide range of foods, as a meat-tenderising agent, for medicinal purposes and as an alcoholic beverage. In addition, the stems and leaves are a source of fibre, which can be processed into paper or cloth, whilst waste materials are used as animal feed. The total world production in 2009 was 18 million t (fruit) from 920 000 ha (FAOSTAT, 2011). Pineapple is the third most important tropical fruit by value, after banana and citrus.

One of the main features of pineapple is its adaptation to areas of low rainfall. It differs from most other commercial crops (except agaves and cacti) in that it has a photosynthetic adaptation (crassulacean acid metabolism, CAM) that facilitates the uptake of carbon dioxide at night. This dramatically improves its water-use efficiency when it is grown under dry conditions.

This chapter begins with a description of the stages of crop development (including roots) in relation to water availability, followed by reviews of plant–water relations,

Figure 12.1 Harvesting a commercial pineapple plantation in Swaziland (MKVC).

Figure 12.2 Intensive horticulture in Kenya – pineapples, fruit trees and *Phaseolus* beans (MKVC).

water requirements and water productivity, and irrigation systems. The physiology of pineapple was reviewed by Bartholomew and Kadzimin (1977). The most recent paper by Malézieux *et al*. (2003) largely repeats the content of an earlier review by the same authors (Batholomew and Malézieux, 1994).

Crop development

There are approximately 30 cultivars of *A. comosus* var. *comosus* that are grown commercially. The international pineapple industry is dominated by cv. ‘Smooth Cayenne’, which is used mostly for processing, and which has been the backbone of the industry for more than a century. Highly specialised systems of production and processing have been developed almost exclusively for this cultivar (Chan *et al*., 2003), but these have since been adapted for cultivar ‘MD-2’, a complex hybrid bred in Hawai’i, which was officially released in 1996, and which is now the world’s principal fresh-fruit-for-export cultivar (Bartholomew, 2009; PIP, 2011b). Cultivar ‘Pérola’ (considered to be drought tolerant) is important in parts of South America, including Brazil, where it is grown on 80% of the planted area (Matos and Reinhardt, 2009). These three cultivars, together with ‘Queen’ (a cultivar that produces small fruit), include 90% of pineapples grown in the world. Cultivars often have local names as well as their generic names (Chan *et al*., 2003; Coppens d’Eeckenbrugge and Leal, 2003).

Vegetative growth

Pineapple, a perennial herb, is propagated vegetatively, using shoots, suckers, slips or tops (Figure 12.3, for definitions see below). A short, thick stem (that stores starch) supports 70–80, closely spaced, succulent leaves. Water droplets (from rain and heavy

Figure 12.3 Pineapple, a perennial herb, is propagated using shoots, suckers, slips or tops (for definitions see text) – Swaziland (MKVC).

dew) are collected by the spirally arranged rosette of leaves and funnelled into the leaf axil cups for absorption by the basal white leaf tissue and the axillary (aerial) root system in the leaf bases (Purseglove, 1972). When fruit is forming in the subtropics, buds in the axils of leaves elongate to form lateral branches, called ‘suckers’, which, if left, develop into a ratoon crop but, if removed, can be used for propagation. Such shoots form after the fruit matures in the tropics, where ratooning is a less common practice. Vegetative branches may arise from the stem below the soil. These are called ‘ground suckers’. They are not used for propagation. Below the inflorescence, buds in the axils of short, modified leaves grow out to form ‘slips’ (rudimentary fruits). Pineapple grown commercially is usually planted in double-row beds at densities of about 60 000 ha^{-1} (for canning) or 75 000 ha^{-1} (for fresh fruit), in many areas into a black polythene mulch (Evans *et al.*, 2002). Densities as high as 120 000 plants ha^{-1} are used in South Africa with cv. Queen. The leaf-area index can reach 9–10 (Bartholomew and Kadzimin, 1977).

From a crop-management perspective, the most important whorl of leaves on a pineapple are the so-called ‘D-leaves’. These are the youngest physiologically mature leaves, usually representing the tallest leaves on the plant from ground level. The relative thickness of a ‘D-leaf’ has been used as an index of the plant water status (Bartholomew and Kadzimin, 1977). Under well-watered conditions, thermal time (daily sum of the mean air temperature less the base temperature for growth, which is 8.3 ℃) has been shown to be a useful predictor of an increase in plant (vegetative) dry weight (Dubois *et al.*, 2010).

There is little information on the effects of water deficits on vegetative growth. Symptoms of drought stress develop slowly, the earliest visible signs being wilting of the lower leaves, followed by leaf colour changes from dark to pale green, then to yellow and finally to red. At the later stages, leaf margins curl downwards and leaves lose their turgidity (Malézieux *et al.*, 2003).

Flowering

Flowering is initiated, at the terminal axis of the stem, by low temperature, water stress or (commercially) induced with ethylene or ethephon, which degrades to ethylene, chlorine and phosphate (known as ‘forcing’). Within a given environment, fruit size is highly correlated to plant size at forcing. Assuming growing conditions are not limiting, the time from planting to forcing at a targeted plant weight is determined by the weight and type of planting material, mostly the former, and by the prevailing temperature. The time may range from six months (in the tropics, where large suckers are commonly planted) to 18 months in the cooler subtropics. The apical meristem then broadens to form a compact inflorescence and inflorescence emergence, called ‘red heart’, usually occurs 30 to 90 days after forcing, with the duration being dependent on the cultivar and prevailing temperature. Each inflorescence contains 100–200 flowers (Figure 12.4). No seeds are produced, unless there is cross pollination, and in commercial production this is avoided. Because the inflorescence is terminal, the formation of new leaves on the main (flowering) axis ceases

Figure 12.4 Inflorescence emergence, called ‘red heart’, usually occurs 30 to 90 days after forcing. Each inflorescence contains 100–200 flowers – Swaziland (MKVC). See also colour plates section.

when reproductive development begins. A minimum plant weight must be reached before natural induction can occur (for ‘Smooth Cayenne’ this is probably at least 1.5 kg fresh weight, Evans *et al*., 2002). Cultivars MD-2, Queen and Pérola are all considered to be sensitive to natural induction of flowering, whereas Smooth Cayenne is insensitive. Sensitivity is a desirable attribute, as it means greater control of flowering is possible. The plant weight at which a plant can be induced to flower, either naturally or ‘forced’, varies with the cultivar and the location (subtropics or tropics). Natural induction rarely occurs in well-grown crops (D.P. Bartholomew, personal communication).

Although the evidence is inconsistent, there is a view that mild water stress (and excess water) can induce flowering in pineapple, but this effect has yet to be quantified in useful ways (Bartholomew *et al*., 2003b)

Fruiting

The parthenocarpic fruitlets that form fuse into a multiple fruit (known as a syncarp), the appearance of which is familiar to all (Figure 12.5). The cluster of small leaves that surmount the fruit are known as the ‘crown’ or ‘top’. The time taken from ‘forcing’ to harvest is temperature dependent, ranging between about 135 days in tropical Ghana to 270 days in Hawai’i (D.P. Bartholomew, personal communication). A model based on the concept of day-degrees has been developed to predict the harvest date of cv. Smooth Cayenne (Malézieux *et al.*, 1994). The model operates in two stages, from ‘forcing’ to the day of opening of the first flower (based on daily maximum and minimum air temperatures), and from then until harvest, defined as when 50% of the fruits are one third yellow (based on fruit temperature). When tested, the model predicted harvest dates for a range of locations with an accuracy of between ±3 d and ±12 d.

Figure 12.5 Pineapple fruit – the parthenocarpic fruitlets fuse into a multiple fruit known as a syncarp. The cluster of small leaves that surmount the top is known as the crown or the top – Swaziland (MKVC).

There are few reports on the effects of drought on fruit development. Both fruitlet number and fruit weight can be reduced by water stress, but the relationships have not been quantified in ways that are useful (Bartholomew *et al.*, 2003b). Fruits that mature under severe water stress are highly susceptible to cracking if rain occurs near maturity (Malézieux *et al.*, 2003).

After harvest, one or sometimes two ratoon crops may be taken. In tropical environments ratoon crops require special techniques (except at low altitude near the equator, where ratoon crops are not possible) (Purseglove, 1972; Bartholomew and Kadzimin, 1977).

Roots

The concept of what constitutes ‘a healthy root system’ (for pineapple) was reported in detail by a group of scientists from the Pineapple Research Institute of Hawai’i (Anderson *et al.*, 1961). All the roots from vegetatively propagated plants originate from just behind the growing point/meristem of the planting material (crowns produce more roots than slips). They grow outwards through the cortex and then remain dormant until the propagule is planted. Roots emerge from the section of the stem in contact with moist soil, and grow into the soil and form main roots. These branch to form lateral roots (both with root hairs) and spread laterally (up to 3 m) and to a soil depth, determined in part by soil porosity and water content, usually of between 0.85 and 1.5 m. As the plant grows, the meristem moves further away from the soil surface and more roots emerge above ground level. These axillary or aerial roots, which are reddish brown in colour, wrap around the stem, where they collect water funnelled from the leaves. It is hard to explain why an extensive axillary root system develops if it does not contribute to water and nutrient uptake. Root growth commences soon after planting and continues until flowering (DPI, 2009; Bartholomew *et al.*, 2003a). There is circumstantial evidence that poor nematode control in the mother plant crop results in failure of the ratoon crop. This supports the belief that development of the ratoon crop depends on an active plant-crop root system (Bartholomew and Kadzimin, 1977).

Summary: crop development

1. Pineapple is propagated vegetatively.
2. Roots on vegetatively propagated plants originate from just behind the growing point: some roots remain above ground level, others grow into the soil, reaching depths of 0.85–1.5 m.
3. Water droplets collect in the axils of the succulent, spirally arranged leaves. The water can be absorbed by basal leaf issue, and by aerial roots.
4. Visible symptoms of drought stress develop slowly.
5. Flowering is initiated at the terminal axis of the short, thick stem; the formation of new leaves then ceases.

6. Parthenocarpic fruitlets fuse into a multiple fruit. It takes 180–270 days from flower initiation to harvest (temperature dependent).
7. Water stress can reduce the number of fruitlets and fruit weight.
8. After harvest, one or two ratoon crops may follow (except near the equator).
9. Root growth ceases at flowering. The ratoon crop depends on the original root system.

Plant–water relations

CAM

In the context of promoting the potential of plants with crassulacean acid metabolism (CAM) on marginal lands, Borland *et al.* (2009) described in detail the biochemistry and regulation processes involved. In the dark, CAM plants open their stomata and perform PEPC (phosphoenolpyruvate carboxylase)-mediated atmospheric and respiratory CO_2 uptake to form malic acid. The malic acid is accumulated in vacuoles and in light is transported from the vacuole and broken down to release CO_2, which is fixed by the enzyme RuBisCO. As a result of CO_2 release into the intercellular spaces, stomata close in response to the elevated CO_2. In C_3 plants RuBisCO mediates the initial fixation of carbon. In C_4 plants PEPC mediates the initial carbon assimilation, but RuBisCO, which is spatially separated from PEPC in bundle sheath cells, fixes the carbon into carbohydrate, both processes occurring in the daylight. The temporal separation of C_4 and C_3 carboxylation underpins CAM. The closure of the stomata in the light and the concomitant, almost complete, cessation of transpiration from the shoot surface explain the high water-use efficiency of CAM plants. Annual above-ground biomass production of CAM plants is comparable with that in C_3 and C_4 crops, but with only 20% of the water required for their cultivation (Nobel, 1991; Borland *et al.*, 2009).

The stomata are open throughout the night, with peak opening at dawn, followed by closure within a few hours after sunrise until mid-afternoon, when they begin to re-open (Bartholomew and Kadzimin, 1977). Most CO_2 assimilation occurs at night (phase 1) and in the late afternoon (phase 4); a small amount is fixed during phase 2 (the beginning of the light period) and, because the stomata are closed, no exogenous CO_2 is assimilated during phase 3 (morning to early afternoon) (Zhu *et al.*, 1999).

Despite the low gas-exchange conductances associated with the succulent tissues, high productivities are achievable by CAM plants in habitats where rainfall is seasonal or intermittent. This is partly because of their capacity to store large quantities of water as a result of having: (a) a ‘dedicated’ water storage parenchyma sap with a corresponding high osmotic potential (close to –1 MPa) and (b) thin (elastic) cell walls. Furthermore, CAM plants can lose 80–90% of their water content and still survive long periods without rain. CAM plants also have the capacity to prevent the reverse flux of water from their storage tissues into the soil. This is achieved by: (a) isolating their roots from the soil (by shrinkage of the root cortex and, in older roots, due to the presence of a sclerified epidermis), together with (b) cavitation in the xylem vessels in the root, whilst

(c) aquaporins (proteins embedded in the cell membrane) in the cortex and endodermis also regulate the flow of water (Nobel, 1988; Borland *et al*., 2009).

Gas exchange

Stomata are found mainly on the underside of pineapple leaves in depressed channels at densities of 70–85 mm^{-2} (Bartholomew and Kadzimin, 1977, citing Krauss, 1949; Malézieux *et al*. 2003). They are relatively small and protected by wax-covered hairs (trichomes), which significantly increase the water vapour path from the mesophyl cells to the boundary layer. For comparison, the average density of stomata for CAM succulents is 27 mm^{-2} (Nobel, 1988). Consistent with these morphological features, stomatal conductances are also much lower in CAM succulents compared with mesophytic plants. When droughted, the stomata close throughout the dark and light, although closure at night may be delayed by several weeks because of the large quantities of water stored in the tissues that act as a buffer (Ting, 1985). Up to half of the cross-sectional area of a mature pineapple leaf is specialised water-storage tissue. Since the stomata are closed when evaporation rates are high, the ratio of carbon gained to water lost is greatly increased (Borland *et al*., 2009).

In a greenhouse study in Japan, Nose *et al*. (1977) showed how the daytime light intensity influences the time when the influx of CO_2 begins in pineapple (cv. Mitsubishi-kei Yuryo Keito (Smooth Cayenne)) and the level it reaches. The greater the light intensity, the earlier in the afternoon ingress begins, and the faster the rate of ingress during the night. In a follow-up paper describing a similar experiment, CO_2 ingress followed a similar time course, regardless of the soil water status (except when the soil was very dry). Transpiration followed a similar pattern, peaking during daylight, before continuing through the night at a reduced rate (Nose *et al*., 1981).

Wild and subsistence varieties of pineapple differ in the degree to which they express CAM attributes. In Thailand, Ritchie and Bunthawin (2010) showed how cv. Phuket, when well watered, behaved more like a C_3 species than a CAM species, as the C_4 carboxylation process that occurred overnight only contributed 2.5% of the daily total of carbon fixed. By contrast, cv. Smooth Cayenne can fix 70–84% nocturnally (e.g. Cote *et al*., 1993). Such a difference between cultivars, if confirmed, has implications in our understanding of water productivity. The proportion of CO_2 assimilation that occurs at night is also affected by environmental factors such as temperature and CO_2 levels, although to a lesser extent. For example, values varied from 69 to 84%, depending on the day/night temperature regime (at ambient CO_2 levels), or from 63 to 68% at elevated CO_2 concentrations (Zhu *et al*., 1999). Plants grown at elevated CO_2 levels had higher instantaneous water-use efficiencies than those grown at ambient levels, both when well watered (*c*. +50%) or when subject to drought (up to ×4), at all three of the day/night temperatures tested (35/25, 30/25 and 30/20 °C), which were chosen to simulate climate change (Zhu *et al*., 2005).

In a review paper on water-use efficiency, Stanhill (1986) cited values for the transpiration ratio (transpiration/mass of above-ground dry matter) for 14 C_4 plants (320 ± 43 g g^{-1}), 51 C_3 plants (640 ± 165 g g^{-1}) and for five CAM species (103 ± 41 g g^{-1}).

The average value for pineapple (the only CAM crop plant listed) was 69 g g^{-1}. Typically, the water-use efficiency of CAM plants, expressed as CO_2 fixed per unit of water lost, may be three times higher than that of C_4 plants (e.g. sugar cane) and at least six times higher than that of C_3 species (Borland *et al.*, 2009).

Summary: plant–water relations

1. Pineapple has a crassulacean acid metabolism (CAM), unlike most other crop plants.
2. CAM plants can survive long periods without rain because of the capacity of the leaf tissue to store water, and because plants are also able to prevent the reverse flow of water from storage tissues into the soil.
3. Stomata are present on the abaxial surface of pineapple leaves in troughs under trichomes at relatively low densities (70–85 mm^{-2}) and small size.
4. The stomata are open throughout the night, and close during the day before re-opening in mid-afternoon. When a plant is droughted the stomata close throughout the day.
5. The proportion of CO_2 assimilation that occurs at night is usually in the range 60–80%.
6. The water-use efficiency of CAM plants is typically three times higher than C_4 plants and six times higher than C_3 species.

Crop water requirements and water productivity

In pioneering work in Hawai'i, Ekern (1964) estimated the average annual water use of pineapple (over a three-year cycle) to be 450 mm for a crop grown with a plastic or paper mulch, but only 300 mm when it was grown in an organic/trash mulch. Using a hydraulic lysimeter, Ekern (1965) showed that the proportion of water loss that occurred at night (2000 h to 0800 h) was nearly three times greater for one-year-old pineapples than that from bare soil, and about twice that from a grass sward, or from a USWB Class A evaporation pan. In a fully developed pineapple crop, direct evaporation from the soil and crop surface (E) is the main component of evapotranspiration (ET) during the daytime.

By contrast, in the hot and humid environment of Paraiba state in Brazil (7° 14′ S 34° 59′ W; alt. 85 m), evapotranspiration (ET) from a pineapple crop (cv. Pérola) only occurred during daylight hours (Azvedo *et al.*, 2007). These authors used the Bowen ratio method to monitor ET from day 140 after planting, when the leaf-area index had reached about 0.5, to day 481 when the plant crop was harvested. Supplementary irrigation was applied by sprinklers 'whenever needed' so that the soil/crop surface was frequently wetted. It is not therefore surprising that the potential evapotranspiration rate (ET_c) was relatively constant over the whole 341 day period almost regardless of the stage of crop development, averaging 4.1±0.6 mm d^{-1} (peak rate 4.6, minimum 3.4 mm d^{-1}). The relative humidity averaged 94%. The reference crop evapotranspiration (ET_o) was calculated using the Penman–Monteith method (Allen *et al.*, 1998). Over the monitored 341-day period, ET_c totalled 1420 mm and ET_o 1615 mm. The crop coefficient K_c ($= ET_c/ET_o$), which also changed little, averaged 0.88±0.06. The high K_c value must have been due to evaporation (E), as a result of the frequent re-wetting of the soil and crop surfaces by rain or irrigation water (although the authors do not mention this), rather than transpiration (T). The fresh fruit weight at harvest was 80 t ha^{-1}, giving a water productivity value, based on ET_c, of 5.6 kg (fresh fruit) m^{-3}. The dry fruit weight was 10 t ha^{-1}.

At the same site in Brazil, De Souza *et al.* (2008) also used the energy-balance (Bowen ratio) method to estimate the latent heat flux from a supplementary-irrigated pineapple crop as it developed with time from planting. Diurnal measurements again showed that evapotranspiration only occurred during the daytime. It began early in the morning at sunrise (*c.* 0700 h) and peaked in the middle of the day (1000–1400 h) before declining and ceasing at sunset (*c.* 1700 h). The leaf area indices on the three days these measurements were made were 7.4, 10.2 and 7.5. The daily latent heat pattern followed closely the net radiation curve, matching changes in the degree of cloudiness. About 76%, 58% and 78% of the net radiation was dissipated as latent heat on each of the three days, respectively.

Using the eddy-correlation technique, San-José *et al.* (2007a) monitored seasonal patterns of carbon dioxide, water vapour and energy fluxes in a rain-fed pineapple crop (cv. Red Spanish) over five consecutive wet/dry seasons in Venezuela (9º 38′ N 63º 37′ W; alt. 195 m). This time the proportion of available energy used for evapotranspiration reached a maximum of 0.84, but declined as the sandy-loam soil dried below field capacity to 0.09. The average transpiration rates (T) were 2.3–2.5 mm d^{-1} in the wet seasons, falling to 0.6–1.0 mm d^{-1} in the dry seasons, with a cumulative total (over 840 d) of 1725 mm (corresponding to 0.39 × USWB Class A pan evaporation). The proportion of the net daily dry matter production accumulated at night varied from 0 to 0.93, but nocturnal CO_2 uptake (CAM) exceeded daytime uptake on fewer than 25 days (i.e. when the ratio was >0.5). With the major part of CO_2 uptake occurring during the daytime, the benefits of CAM (and reduced transpiration) were constrained (San-José *et al.*, 2007b). Water-use efficiencies, based on transpiration, averaged 1.0 kg carbon m^{-3} for total dry matter production and 0.14 kg carbon m^{-3} for fruit (equivalent to 11 kg fresh fruit m^{-3}).

Although Thorne (1953) was a pioneer in researching the role of irrigation (and trash mulch) in pineapple production in Hawai'i, Bartholomew and Kadzimin (1977) were unable to identify any publications of research outputs relating water supply to growth or yield of pineapple. In 2003, 26 years later, despite commercial experience indicating the benefits of irrigation, Malézieux *et al.* (2003) could again not find any research reports indicating the advantages to be gained from irrigation, or the losses due to water stress. Most of the data on the effects of water stress on growth have been obtained on plants grown in pots and has limited commercial or scientific value (e.g. Chapman *et al.*, 1983).

In the FAO crop evapotranspiration manual, Allen *et al*. (1998) specified the following K_c values for pineapple: the initial stage, $K_c = 0.50$; mid-season, $K_c = 0.30$; end-season, $K_c = 0.30$ (all values assume that 50% of the ground surface is covered with black plastic mulch, as practised in Hawai'i). The explanation given for the low values was as follows:

> *The pineapple has very low transpiration because it closes its stomates during the day and opens them during the night. Therefore, the majority of ETc from pineapple is evaporation from the soil. The Kc mid < Kc ini since Kc mid occurs during full ground cover so that soil evaporation is less. For drip irrigation beneath plastic mulch the Kc' values given can be reduced by 0.10.*

Based on the (limited) evidence cited here it is not immediately clear on what basis these K_c values were derived, since, for well-watered pineapple crops, K_c has maximum values of 0.8–0.9. Indeed, Souza and Reinhardt (2007) even suggested that, for a crop with 100% ground cover, $K_c = 1.0$–1.2, which would appear to be excessive.

Again based on very little evidence, Doorenbos and Kassam (1979), estimated (guessed?) the water productivity of pineapple yielding 75–90 t ha^{-1} fresh fruit to be 5–10 kg m^{-3} for the plant crop and 8–12 kg m^{-3} for the first ratoon (based on irrigation water applied). By comparison, the figures cited above were 5.6 kg (fresh fruit) m^{-3} (based on ET_c) in Brazil (Azvedo *et al*. (2007), and 11 kg (fresh fruit) m^{-3} (based on transpiration) in Venezuela (San-José *et al*., 2007b)

Summary: crop water requirements and water productivity

1. In general, pineapple requires a minimum monthly rainfall total of 50–100 mm.
2. Considering its special (CAM) attributes, there are surprisingly few published reports of field measurements of crop water use and water productivity of pineapple.
3. According to most reports, and compared with other crops/surfaces, pineapple uses a disproportionate amount of water at night, but some reports suggest that *ET* only occurs during the daytime.
4. For a frequently sprinkler-irrigated crop in Brazil, ET_c averaged 4 mm d^{-1}, almost regardless of its stage of development; the crop factor (K_c) was correspondingly high (0.88).
5. In Venezuela, the proportion of available energy used for evapotranspiration from a rain-fed crop reached 0.84, declining to 0.09 as the soil dried.
6. In Venezuela, actual transpiration rates recorded during the wet season averaged 2.3–2.5 mm d^{-1}, falling to 0.6–1.0 mm d^{-1} in the dry season.
7. In Venezuela, over an 840-day period (wet and dry seasons), CO_2 uptake occurred mainly during the daytime. Nocturnal uptake only exceeded daytime uptake on 25 days.
8. Water productivity values identified in the Brazilian and Venezuelan reports are not directly comparable: 5.6 kg (fresh fruit) m^{-3} (based on ET_c), and 11 kg (fresh fruit) m^{-3} (based on transpiration).

Irrigation systems

In Hawai'i it became profitable to irrigate pineapple when the switch from cannery production to fresh fruit production occurred. Irrigation then became essential in order to ensure continuous all-year-round production. This switch involved, for example, planting every week, so irrigation was then needed to establish the crop. Managing and maintaining crop schedules is critical for fresh fruit production (D.P. Bartholomew, personal communication).

In Hawai'i, pineapple is grown in beds covered with plastic mulch to prevent the volatisation of nematicides injected into the soil to control plant-parasitic nematodes. Usually two rows of pineapple are planted into each sheet of plastic (Figure 12.6). There, irrigation by the drip system to supplement rainfall is becoming the standard practice (since the switch to fresh fruit production). The tubing is laid in the centre of

Figure 12.6 Sometimes pineapple is planted through a plastic or paper mulch, partly to conserve water – Uganda (HDT).

each bed beneath the plastic mulch, with one emitter supplying water to every two plants. According to Hawai'ian sources, a single irrigation by sprinklers is recommended in order to aid crop establishment immediately after planting, during dry weather. Whereas drip irrigation can continue until just prior to harvest, overhead (sprinkler) irrigation should be avoided after the onset of the open petal stage of flowering to help control fruit diseases. Evenly distributed rainfall (or irrigation) of 600 mm per year is considered to be adequate for maximum growth. (Evans *et al*., 2002; Hepton, 2003; University of Hawai'i, 2011). Herbicides that are broadcast over the whole area get washed off the plastic by rain and/irrigation water from sprinklers and concentrated into the open, uncovered areas between the sheets of plastic (Dusek *et al*., 2010).

Drip irrigation is used where the water supply is restricted, the cost of labour is high and cultivation techniques are advanced. Micro-jets can also be used, as can any of the overhead sprinkler systems, depending on local circumstances. For example, rain guns and booms attached to hose reels are used to irrigate pineapples in Indonesia, Ghana, South Africa and Thailand (D.P. Bartholomew, personal communication).

Cover crops such as *Pennisetum americanum* and *Cynodon dactylon* are recommended in Brazil as part of an integrated pineapple production system, primarily for weed control, but with the trimmings acting as mulch, protecting against soil erosion, and conserving soil water (Matos and Reinhardt, 2009).

General conclusions

Citing others, Almeida *et al*. (2002) stated that, in general, pineapple requires a minimum monthly rainfall total of 80–100 mm. Where the annual rainfall is less than 500 mm, irrigation is essential. If it is above this threshold irrigation is still needed if there are three consecutive months with monthly rainfall of less than 15 mm, or four consecutive months with less than 25 mm month^{-1} or five months with less than 40 mm month^{-1}. In Hawai'i, for example, there is a four-month summer dry season when rainfall averages only 25 mm month^{-1} (Bartholomew and Kadzimin, 1977). These appear to be the best guidelines available to pineapple growers contemplating whether or not to invest in irrigation (other than for crop establishment). There is a similar lack of detailed advice on the yield and quality benefits/penalties that result from the application of good/poor water-management practices. Nevertheless, although pineapple is mainly a rain-fed crop, it is widely irrigated, for example in Hawai'i and in Brazil, where 20% of the cropped area is irrigated (≡ *c*. 12 000 ha) (Silva, 2011).

There is little doubt that CAM plants, in general, can survive/tolerate dry conditions (details as yet unspecified) or areas with erratic rainfall. There is more uncertainty about the actual water use of pineapple, and relative rates of water loss (transpiration) and carbon gain (net photosynthesis), during the daytime and at night, under different water regimes. This is surprising, given the importance of pineapple, not only as a local product providing livelihoods for numerous households (Figure 12.7), but as an internationally traded commodity, and also because of the amount of fundamental research reported on photosynthesis of CAM plants in general. There has been a similar lack of

Figure 12.7 Pineapples for sale in local fruit stall in Sri Lanka (HDT).

emphasis on the water relations of sisal, another important CAM crop plant (Carr, 2012b). As a result, there is no agreed consensus in the literature on the values of the crop coefficient or on water productivity for pineapple. The large-scale private companies have no doubt developed their own criteria for justifying and managing the irrigation of pineapples.

Summary

The results of research on the water relations and irrigation needs of pineapple are collated and summarised in an attempt to link fundamental studies on crop physiology to irrigation practices. Background information on the centres of origin (northern South America) and of production (Brazil, Thailand and the Philippines) of pineapple is followed by reviews of crop development, including roots, plant–water relations, crop water requirements and water productivity, and irrigation systems. The majority of the recent research published in the international literature on these topics has been conducted in the USA (Hawai'i) and Brazil. Pineapple differs from most other commercial crops in that it has a photosynthetic adaptation (crassulacean acid metabolism, CAM) that facilitates the uptake of carbon dioxide at night, and improves its water-use efficiency under dry conditions. The crop is propagated vegetatively. The succulent leaves collect (and store) water in the leaf axils, where it is absorbed by surrounding tissue or by aerial roots. There is little published information on the effects of water deficits on vegetative growth, flowering or fruiting. Water stress can reduce the number of fruitlets and the fruit weight. After harvest, one or two ratoon crops can follow. Roots originate from just behind the stem growing point, some remaining above ground (aerial roots), others entering the soil, reaching depths of 0.85–1.5 m. Root growth ceases at flowering. The ratoon crop depends on the original (plant crop) root system, including the axillary roots. Stomata are present on the abaxial leaf surfaces at relatively low densities (70–85 mm^{-2}). They are open throughout the night, and close during the day before reopening in mid-afternoon. The degree to which CAM attributes are expressed depends in part on the location (e.g. tropics or subtropics), and possibly the cultivar, with the total amount of carbon fixed during the night varying from $<3\%$ to $>80\%$. There are surprisingly few published reports of field measurements of crop water use and water productivity of pineapple. Two reports show evapotranspiration only occurring during the daytime. There is more uncertainty about the actual water use of pineapple, the value of K_c, and relative rates of water loss (transpiration) and carbon gain (net photosynthesis), during the daytime and at night, under different water regimes. This is surprising, given the amount of fundamental research reported on photosynthesis of CAM plants in general. Although pineapple is mainly a rain-fed crop, it is widely irrigated. Drip irrigation is successfully used where the water supply is restricted, the cost of labour is high and cultivation techniques are advanced. Micro-jets can also be used, as can any of the overhead sprinkler systems, providing wind distortion is not a problem. There is a lack of reliable published data quantifying where irrigation of pineapple is likely to be worthwhile, how it is best practised and the benefits that can be obtained. This is remarkable considering the importance of pineapple as an internationally traded commodity.

13 Synthesis

Each fruit crop reviewed in this book is grown in what we loosely describe as the tropics and subtropics. Each has its own unique features and each is of international commercial importance to greater or lesser extents. All of them are locally important and contribute to the livelihoods of millions of people. In this chapter, an attempt is made to:

- compare and contrast the characteristics of each crop,
- review the reporting of research findings, and
- highlight the global challenges to sustainable water management.

Crop comparisons

Summaries of the main findings from the review process are presented for ease of comparison in Tables 13.1 (centres of origin and production), 13.2 (stages of crop development), 13.3 (plant–water relations) and 13.4 (water productivity) for each crop. Also included in these summary tables for comparison are the two fruit crops, banana and coconut, reviewed in the first book in this series (Carr, 2012a).

Centres of origin and production

There are five broad geographic regions in which these 13 fruit crops probably originated (Table 13.1):

- South-east Asia (*banana*, *Citrus*, *lychee* and *mango*),
- South America (*cashew*, *passion fruit* and *pineapple*),
- West Asia (*date palm* and *olive*),
- Central America and Mexico (*avocado* and *papaya*), and
- Australasia (*coconut*, in the Pacific islands, and *macadamia* in Australia).

In contrast to the plantation crops the *centres of production* of these fruit crops have, in general, remained close to the *centres of diversity*. The exceptions are: *Citrus*, which crossed continents and moved west from South-east Asia to Mexico, Chile and the USA, and *cashew* and *papaya*, which went in the reverse direction from Brazil to Vietnam and India.

Table 13.1 Centres of origin and production: summary table for 13 fruit crops

Crop	Region of origin	Principal producing countries	Harvested area (ha × 10^6) and worldwide production (2010)	Farming system	Research centres	Principal products	Shade-adapted (ecological origin)
Avocado	Mexico and Central America	Mexico, Chile, Indonesia Warm subtropical areas, as well as the tropical highlands and humid tropics	0.47 3 million t	Commercial orchards	Australia, California, Israel and South Africa	Fresh fruit	Yes Understorey highland rainforest species
Banana	SE Asia	India, China, the Philippines	4.8 95 million t	Small subsistence farms, plantations	South Africa, Australia, Brazil	Fruit, fresh or cooked Building material, ropes; brewing	No River margins in rainforest
Cashew	Brazil	Vietnam, India	4.0 3.59 million t	Smallholders, large estates	Brazil, Australia	Nuts (edible kernels) Cashew shell nut oil 'Cashew apple' juice	No Savanna or coastal zones
***Citrus* spp.**	SE Asia	Brazil, USA, India	5.4 (4.2 = orange) 86 million t	Orchards, plantations	Spain, Uruguay	Fresh fruit, juices, jams, pectin	Yes Dry monsoon areas

Coconut	SW Pacific/ Indian Ocean islands	Indonesia, the Philippines, India.	11.2 10 million t copra; 6 million t oil	Small farms/ subsistence	Brazil, S. India, Sri Lanka, Côte d'Ivoire	Copra (oil) Oil Building materials	No Coastal areas
Date palm	Mesopotamia (southern Iraq)	Egypt, Saudi Arabia, Iran (Iraq)	1.20 7.9 million t	Mixed oasis planting; intensive orchards	Saudi Arabia, Tunisia	Fresh fruit (a berry) Building material Cultural significance	No Arid areas
Lychee	South China, North Vietnam	China, India	*c*. 0.79 2.2 million t	Smallholders Large orchards in China	Australia, South Africa, Israel	Fresh fruit, some dried	Yes, when young seedlings; not when older
Macadamia	Australia	Australia, Hawai'i (USA), Central America, southern Africa	(*c*. 0.05) 90–100 000 t	Small orchards, larger plantations	Australia, (was Hawai'i, USA)	Nuts (edible kernels)	Yes Understorey spp.; fringes of subtropical rainforests
Mango	SE Asia and India	India, China, Thailand	4.95 37 million t	Single trees to large estates	Australia, Brazil, South Africa, Spain, Thailand, USA (Florida)	Fruit, fresh or processed; leaves vegetable or stock feed Cultural significance	No Tropical, canopy layer forest spp. /subtropical monsoon areas

Table 13.1 *(cont.)*

Crop	Region of origin	Principal producing countries	Harvested area (ha × 10^6) and worldwide production (2010)	Farming system	Research centres	Principal products	Shade-adapted (ecological origin)
Olive	Coastal areas of eastern Mediterranean	Spain, Italy, Greece and countries surrounding Mediterranean Basin	9.5 20 million t	Subsistence farmers, small orchards, larger plantations	Spain, Argentina, Australia, Italy, Morocco, New Zealand, Tunisia, Portugal	Oil Table olives (fresh fruit) Wood carving	No Coastal areas
Papaya	Southern Mexico and neighbouring countries	India, Brazil, Indonesia	0.44 11 million t	Single 'trees', intensive orchards	Brazil Guam (USA)	Fresh fruit, soft drinks, jams Papain (enzyme)	No? Not found in the wild
Passion fruit	Brazil	Brazil, Ecuador, Colombia and Peru	*c.* 1.0 857 000 t	Numerous small orchards, larger plantations	Australia, Brazil	Fruit, juices, puree	Yes Edges of rainforest
Pineapple	Northern South America	Brazil, Thailand, Philippines	0.92 18 million t	Smallholders, large plantations	Hawai'i (USA), Brazil	Fresh fruit, canned, juice; + many ancillary uses	Yes Forest floor

Figure 13.1 Traditional olive grove, Andalusia, Spain – (EF).

Assuming that the recorded areas of each of these crops are reasonably accurate, the most important crop (judged by the harvested area) is *coconut* (11.2 million ha), followed by *olive* (9.5 million ha, Figures 13.1 and 13.2), *Citrus* (5.4 million ha, of which orange occupies 4.2 million ha), then equal fourth *mango* and *banana* (with plantain) with 4.95 and 4.8 million ha respectively and, in sixth and seventh places, *cashew* (4.0 million ha) and *date palm* (1.2 million ha), with 1.0 million ha of *passion fruit*. The remaining five species have a total area of under three million ha, making a combined total of about 45 million ha. For comparison, there are 22.7 million ha of *sugar cane* in the world and 11.7 million ha of *oil palm* and a massive 225 million ha of *wheat*, the most widely grown crop. The harvestable areas need to be treated with caution, since tree density is very variable, and this can lead to misleading estimates of actual crop area. Double counting is always a possibility.

The ecological conditions under which these fruit crops originated are still being debated. Several of them evolved as substorey species in low-latitude, evergreen forests and, as a result, have many of the characteristics of being shade adapted (e.g. *avocado*, *lychee* and possibly *mango*). Other crops are thought to have evolved at the forest edge (*macadamia*, *passion fruit*), the forest floor (*pineapple*) or at river margins (*banana*). Others originated near the coast (*coconut*, *cashew*, *olive*), in drier-monsoon areas (*Citrus*) and in arid areas (*date palm*). The origin of *papaya* is not known.

Figure 13.2 Modern, newly planted, high-density olive grove – Andalusia, Spain (EF).

Shoot and root growth

There is diversity in crop structure and development, but some similarities, among the crops represented here (Table 13.2). For example, both palms (*coconut* and *date palm*) have a stem that develops from a single apical meristem, and which acts as a water store. The stem of *papaya* also stores water. In *pineapple* water is stored in the leaves.

Avocado, *cashew*, *lychee*, *macadamia* and *mango* are all large, evergreen trees in which vegetative growth occurs in a series of flushes interrupted by quiescent periods. There is no convincing evidence with any of these species of a link between the cycle of shoot growth and rates of root extension. In the case of *lychee*, root growth is slow during bud break and early shoot extension. *Citrus* spp. are small, evergreen shrubs or trees, in which shoot growth also occurs in a series of flushes, partly triggered by a rise in temperature (subtropics) or relief of water deficit (tropics). The roots of some grow throughout the year (*avocado*, *lychee* and *mango*), predominantly in the autumn (*macadamia*) or cease growing in the summer (*olive*), at flowering (*banana*), or grow less fast in the winter (*date palm*). In the case of *pineapple*, roots grow throughout the period from planting to flowering, whilst the ratoon (follow-on) crop depends on the original root system of the plant crop. Where it has been measured, root dry mass represented 26–30% of the total plant biomass (*olive* and *macadamia*).

Roots of *avocado*, *banana*, *citrus*, *macadamia* and *pineapple* have been traced to depths of 1.2 to 1.5 m, whilst those of *date palm* (>2 m), *lychee* (>2 m), *olive* (>2 m)

Table 13.2 Stages of crop development: summary table for 13 fruit crops

Crop	Vegetative	Inflorescence	Fruit	Roots		Initial drought symptoms
				Root distribution	Root growth	
Avocado	Evergreen, monopodial trunk & branches, up to 20 m tall; shoot growth in mature trees is synchronised into flushes	Flower initiation occurs in the autumn, with flowering in late winter and spring; flowers form on the ends of well-lit branches; a large tree may have over a million flowers	200–300 fruits/tree; fruit shedding during the first three to four weeks after fruit set and again in early summer	Depth >1.5 m; greatest density 0–0.6 m; maximum observed 3.3 m; horizontal spread 2.5 m	Continues throughout the year; alternating shoot and root growth flushes on 30–60 d cycle	Necrotic lesions occur on cheeks of fruit, continuous at blossom end
Banana	Giant perennial herb; 'apparent' aerial shoot (pseudostem) develops on rhizome	Floral initiation occurs after 30–40 leaves produced; bunch emergence on erect aerial stem; drought reduces flower numbers	Drought reduces fresh weight of fruit and delays maturity	Maximum depth 1.0–1.5 m; effective depth 0.4–0.6 m; spread 2–3 m; water uptake recorded at a depth of 1.8 m	Seasonal/temperature dependent; ceases at flowering	Rate of leaf extension declines
Cashew	Two types of evergreen trees: 'Talls' and 'Shorts' (low spreading); vegetative growth in series of flushes	Flowers form annually on the end of branches in the dry season; hermaphrodite or male; up to 1600 flowers per panicle; duration of flowering is location dependent (2–4 months)	It takes about 2 months from pollination to maturity of nut; harvesting can last 10–12 weeks; premature fruit abscission can occur; prone to alternate bearing	Roots (of rootstock) can extend to depths >5 m; water extraction to 4 m, also wide spreading > 7 m from trunk (2 × canopy)	Not reported	Stomatal closure

Table 13.2 *(cont.)*

Crop	Vegetative	Inflorescence	Fruit	Roots		Initial drought symptoms
				Root distribution	Root growth	
Citrus	Small evergreen shrubs or trees; continual leaf replacement; shoot growth in series of flushes, initiated by rise in temperature (subtropics) or relief of water stress (tropics)	Specific requirements for ‘rest period’ to initiate flowering are not understood; in subtropics flowering occurs in spring, profuse, but <1% flowers produce mature fruits, numbers reduced by abscission, enhanced by water stress	It takes 7–14 months from flowering to fruit maturity; water deficit during fruit expansion phase reduces fruit size, can also trigger secondary flowering	Some uncertainty; general rule roots extend to *c.* 1.5 m; fibrous roots occur in bunches on structural roots, greatest mass in top 0.4 m; roots interconnected; roots are main resistance to water flow in plant	Minimum temperature for root growth *c.* 6 °C; optimum *c.* 26 °C; maximum *c.* 37 °C.	Midday stem water potential falls below –1.3MPa; correlated with stem shrinkage
Coconut	A palm: single stem develops from apical meristem, dwarf and tall types; stem acts as water store; leaves differentiated one at a time 30 months before emergence	Single inflorescence born in axil of each leaf; inflorescence initiated 44 months before fruit is harvested	Drought causes immature fruits and later maturing nuts to be shed	Adventitious; can reach depths from 2 to 4 m; densest top 0.5–1.0 m; lateral spread >3 m.	Not recorded	Drought increases rate of frond shedding and slows emergence of new leaves

Date palm	Xerophyte palm; single stem develops from apical meristem; stem acts as water store; 10–30 new leaves produced each year; terminal crown contains 100–120 leaves.	Trees are dioecious; on female trees inflorescences develop from flower buds in axils of leaves that developed in previous year; each contains 8000–10 000 flowers	It takes 150–200 days from pollination (by hand) to fruit maturity; four distinctive ripening phases; soft dates and hard dates; productive tree can support at least 30 bunches	Fibrous root system, dense in top 0.25 m; roots can extend to depths >2 m; roots contain air spaces; tolerates waterlogging	Roots of (other) palm spp. grow throughout the year, but less fast in winter; no evidence of alternating shoot and root extension growth	Dry fronds
Lychee	Medium to large stocky evergreen tree, with large canopy; vegetative growth in series of flushes; vegetative shoots promoted at temperatures >15 °C	Terminal inflorescences form on current year's growth; initiation and development of floral buds occurs during the winter ($T < 15$ °C) in subtropics only; flowering & yield can be enhanced by water stress in areas with dry winters; flowering is erratic	Prolonged water deficit from flowering reduces yield & increases splitting; fruit harvested late summer; low yielding; no fruits in tropics below 300 m altitude	Water is extracted from soil depths of > 2 m	Very limited evidence of link between cycle of leaf flushes and root extension; root growth continues throughout year, but is highly variable	Leaf water potential
Macadamia	Tall evergreen tree; vegetative growth in series of flushes; compensatory vegetative growth occurs after relief	Floral initiation occurs on hardened wood inside canopy in late autumn; flowering *c.* 150	Water deficit can prevent pollination; high temperatures (>30 °C) and water stress induce	Most fibrous roots found in top 0.4 m; taproot can reach depth of 1.2 m; dense clusters of rootlets (proteoid)	Roots grow predominantly in autumn; they represent about 28% of total biomass	Stomatal closure

Table 13.2 *(cont.)*

Crop	Vegetative	Inflorescence	Fruit	Roots		Initial drought symptoms
				Root distribution	Root growth	
	of water stress; leaves wth xeromorphic adapatations	days later in the following spring; up to three flowering peaks; >10 000 inflorescences per tree each with 200–300 flowers	premature nut drop; only 5–10% flowers set fruit, as few as 0.3% reach maturity, six months later; uneven distribution of fruit in canopy	increase surface area of root system		
Mango	Tall, long-living, indeterminate, evergreen tree; vegetative growth occurs in a series of flushes; excess vegetative growth has to be controlled; base temperature for shoot extension *c.* 15 °C	Flowers form on panicles that are initiated in dormant apical buds, which developed from lateral buds that had flowered the year before; in the subtropics, flower buds are initiated during the cool winter months; if warm, undifferentiated buds will become vegetative; in the tropics, flower buds are initiated after a period of water stress	Only 10% of the flowers set fruit and of these *c.* 80% are shed in the following 4 weeks; <1% flowers reach maturity; avoid water stress at this time; it takes 3–4 months after fruit set for fruit to reach maturity; biennial bearing	Roots can reach depths of 5 m; prolific in top 0.25 m	Roots grow more or less continuously; no link with shoot growth	Changes in stem thickness

Olive	Xerophytic evergreen tree; leaf adaptations protect against water loss; trunk expansion sensitive to water deficit	Period of low temperatures required to induce flowering; *c.* 10 weeks < 12 °C; inflorescences develop from buds in axils of leaves formed on previous year's wood; water stress during inflorescence development reduces number of flowers, and during flowering causes flowers to dry	Less than 2% of flowers set fruit. It takes *c.* 15–18 months from flower bud initiation to fruit maturity; fruits are distributed irregularly in canopy; biennial bearing, 'on' and 'off' years; irrigation can increase fruit size	Roots can extend to depths of at least 2 m; 70% in top 0.5 m	Root growth virtually ceases during summer; at same time shoots and fruits are expanding rapidly; roots represent 26–30% of biomass	Stomatal closure; stem expansion slows
Papaya	Short-lived large herb; leaves emerge from upper part of unbranched (hollow) stem; stem and leaves contain latex; vulnerable to wind damage	After a 2-month juvenile period, flowers begin to develop in leaf axils; flowering (and fruiting) continues as new leaves emerge throughout the year; dioecious trees with male, female or bisexual flowers occur	Trees bear fruit within year after planting, taking 4–6 months from flowering; high yields sustained for 2 years before declining	Roots can reach depths of 0.75 m; 'effective depth' up to 0.55 m	No records	Leaf area declines, fruits shrink, new internodes for flowers are compressed; stomata sensitive to dry air

Table 13.2 *(cont.)*

Crop	Vegetative	Inflorescence	Fruit	Roots		Initial drought symptoms
				Root distribution	Root growth	
Passion fruit	Vigorous, woody perennial climber, with tendrils; supported on wire trellises	A single flower bud develops at each leaf node of new growth, except when there is a water deficit; Heavy rain (or irrigation) at flowering prevents pollination	Bears fruit within 6–8 months after planting; fruit matures 60–90 days after fruit set; harvesting continues throughout the year, with two or three peaks	There is no published evidence to support the view that passion fruit is shallow rooted; most roots found in top 0.5 m; some roots extend to >1 m	No records.	Leaf production and expansion sensitive to water deficit; young leaves become yellow/green; terminal shoots, young leaves and tendrils wilt at midday
Pineapple	Xerophytic perennial herb; short thick stem supports 70–80 closely spaced succulent leaves; water is collected in axils of leaves and absorbed; forms suckers	Flowering is initiated at terminal axis of short thick stem by low temperature, mild water stress or artificially, leaf production then ceases; inflorescence contains 100–200 flowers	No seeds formed; fruitlets merge to form multiple fruit; water deficits reduce the number of fruitlets; it takes 1135–1270 days from flower initiation to harvest	All the roots originate from just behind the growing point and grow into wet soil; main roots branch to form laterals; lateral spread up to 3 m, extending to depths of 0.85 to 1.5 m	As the meristem grows above the soil surface, aerial roots develop; these collect water funnelled from leaves; root growth continues from planting until flowering; ratoon crop depends on original plant crop's root system	Visible symptoms of drought develop slowly

coconut (2–4 m), *mango* (5 m) and *cashew* (>5 m) can reach greater depths. The greatest density of roots can normally be found in the top *c*. 0.5 m of soil, sometimes extending to 1 m. Roots are prolific in the surface 0.25 m. Roots of *papaya* (0.75 m) and *passion fruit* tend to go less deep (<1 m). Lateral spread depends on tree spacing. *Cashew* roots have been traced as far as 7 m from the trunk (a major reason for its capacity to survive dry weather), with *coconut*, *olive* and *pineapple* >3 m. Fibrous roots occur as bunches on structural roots in *Citrus*, and proteoid roots can be found on *macadamia*. Both these adaptations increase the surface area of roots in contact with the soil. Although the *date palm* is a xerophyte, the roots have air spaces, which contribute to their capacity to withstand waterlogged conditions. These rooting depths and distributions should be considered as indicative only as many soil physical factors influence root distribution.

Flowering and fruiting

Factors stimulating flower initiation are not yet fully understood. Each species responds in a different way. In the subtropics, seasonal differences in temperature play an important role in the time of flower initiation and flowering. For example, with *avocado*, *Citrus*, *date palm*, *lychee*, *macadamia*, *mango*, *olive* and *pineapple*, flower initiation occurs in the autumn or early winter. Prolific flowering then follows in the spring. In the tropics, a water deficit and/or the switch from dry to wet conditions, at the end of the dry season, will trigger flower formation in *Citrus*, *mango* and *pineapple* (or in some cases improve it, e.g. *lychee*, but only if it is followed by cool weather).

Cashew flowers form during the dry season and, when well supplied with water, flowering can continue throughout the year. Other fruits that flower continuously are *coconut*, *papaya* and *passion fruit*. In *banana*, floral initiation occurs when a certain number of leaves have emerged, and this can occur at any time during the year.

The flowers develop on different parts of the plant, for example on/in:

- the axils of leaves: *Citrus*, *coconut*, *date palm* (but only on leaves that developed the previous year), *olive* (on leaves that developed on wood formed the year before), *papaya* (female flowers) and *passion fruit*;
- terminal and axillary buds on hardened wood within the canopy: *macadamia*;
- terminal branches: *avocado*, *cashew*, *lychee*;
- dormant apical buds on new shoots that developed from lateral buds on stems that flowered the year before: *mango*;
- the apical meristem: *pineapple*;
- an erect aerial stem: *banana*.

The time taken for a fruit to mature also varies between species. For example, the time interval between floral initiation and harvesting a mature *coconut* is more than three years, for *olive* 15–18 months and for *lychee* between five and eight months. From pollination to maturity in the *coconut* takes 12 months, *Citrus* 200–400 days (varies with species), *macadamia* about 210 days, *date palm* 150–200 days, *papaya* 120–180 days, *olive* 120–150 days, *mango* 90–120 days, *lychee* 80–110 days, *passion fruit*

60–90 days and *cashew* only 60 days. *Banana* is not pollinated. These differences are critical when trying to assess the effects of water stress at different growth stages. The weather can have a big impact on crop development processes over a 12-month period (*coconut*), compared with, say, 60 days (*cashew*).

Shedding of large numbers of immature fruits occurs with many of the crops described (e.g. *avocado*, *cashew*, *Citrus*, *macadamia* and *mango*). This process is usually made worse by water stress, but in the case of *lychee*, shedding can be reduced by moderate water stress. A characteristic of some crops (e.g. *avocado*) is that fruit drop is not limited to the very young stages (as in *Citrus*), but continues for a long period, even when fruits are about half final size (Elias Fereres, personal communication).

Plant–water relations

Of the 13 fruit crops described, only *banana*, *Citrus* and *date palm* have stomata on both leaf surfaces (Table 13.3). With *banana*, the density on the *abaxial* or lower surface (130–170 stomata mm^{-2}) is about four times that on the upper surface (35–50 mm^{-2}). For *Citrus* the corresponding densities are 800 and 40 mm^{-2} respectively. Some of the stomata on *Citrus* leaves are blocked with wax plugs, especially on the upper surface. The distribution of stomata between the two surfaces is about even for *date palm*. The remaining 10 crops only have stomata on the abaxial leaf surfaces, at densities ranging between 200 mm^{-2} (*coconut*), 350 mm^{-2} (*avocado*, some of which are also blocked with wax), up to 700 mm^{-2} (*mango*). These numerical comparisons assume that the leaves were at similar stages of development when assessed, with similar life histories. Leaves of different sizes will have different stomatal densities, whilst leaves developing in the dry season will have different densities from (similar) leaves developing in the rainy season.

Stomata are also present on *Citrus* fruit at densities of *c*. 70 mm^{-2}. *Lychee* also has stomata on green fruit. *Avocado* has stomata on its floral parts. In the case of *olive*, the stomata (420–540 mm^{-2}) are located beneath a trichome layer (peltate hairs). The stomata are located in depressions within the leaves of *pineapple*, but at much lower densities (70–85 mm^{-2}) and they are also smaller in size than they are with other crops.

Stomatal conductance is a good indicator of soil water availability and plant water status in *banana* and possibly also in *avocado*. The stomata of many of the crops are sensitive to changes in the dryness of the air, beginning to close when the saturation deficit exceeds about 1.5–2.0 kPa (e.g. *cashew*, *Citrus*, *coconut*, *lychee*, *mango*, *papaya* and, probably, *olive*), or less than this (*lychee*). The stomata of *pineapple* are open at night and closed for most of the day, but it is not yet clear what proportion of CO_2 assimilation occurs during the night compared with during daylight hours. There is evidence of cyclic oscillation in *Citrus*. Leaf water potential is a good indicator of plant water status in *coconut* and *lychee*, but poor in *banana*. Because of latex exudation it is not easy to use a pressure chamber to measure leaf water potential in *mango*. Sap-flow measurements have been successfully used to monitor transpiration by individual *avocado*, *cashew*, *date palm*, *mango*, *olive* and *papaya* trees.

Table 13.3 Plant–water relations: summary table for 13 fruit crops

Crop	Stomatal density	Conductance	Leaf water potential	Photosynthesis	Transpiration	Other indicators of plant water status	Drought resistance indicators
Avocado	Abaxial 350–510 mm^{-2}, blocked by wax; leaves develop a waxy cuticle on both surfaces; also present on floral parts and young fruit	Stomatal conductance begins to decline when the leaf water potential falls below –0.4 MPa, and continues to decline until it reaches –1.0 to –1.2 MPa, when the stomata are fully closed	Leaf water potentials remained constant (–0.5 MPa) over ET_o range 7–15 mm d^{-1}; osmotic potential declines with onset of drought	C_3 Decline in stomatal conductance is accompanied by a parallel reduction in net photosynthesis; water stress also induces changes in leaf anatomy, reduces photosynthesis	Maximum rate of transpiration was only 3 mm d^{-1}, even when potential evapotranspiration (ET_o) rates were large (7–15 mm d^{-1}). The ratio T/ET_o was always small (0.13–0.21)	Stomatal closure is an early indicator of water stress?; droughted plants develop tyloses in xylem vessels	Differences exist between the races and genotypes in the susceptibility of the xylem vessels to cavitation
Banana	Abaxial up to 4× adaxial; 130–170 / 35–50 mm^{-2}	Good indicator of soil water availability & plant water status	Poor indicator of plant water status; diurnal range 0 to –0.35 MPa only	C_3 Soil water potential (Ψ_m) not $<$ –33 kPa at 0.2–0.3 m depth	Limited by dry air $>$ 2–2.3 kPa	Leaf extension rate; refractive index of exuded latex	Presence of B genome
Cashew	Not recorded	Progressive closure of the stomata occurs at saturation deficits >1.5 kPa	Leaf water potentials at 0930 h remained relatively constant at –1.2 MPa in non-irrigated trees, but declined to –1.5 MPa in irrigated trees	C_3 Increase in saturation deficit of air (up to 3.5 kPa) does not appear to influence rates of CO_2 assimilation	Sap-flow rates of 20–28 L d^{-1} tree^{-1} have been recorded	Stomata play an important role in maintaining favourable leaf water status under dry conditions	In the field, differences in rates of photosynthesis and transpiration between irrigated and unirrigated trees only apparent three to four months after the end of the rainy season, when the air was dry

Table 13.3 *(cont.)*

Crop	Stomatal density	Conductance	Leaf water potential	Photosynthesis	Transpiration	Other indicators of plant water status	Drought resistance indicators
Citrus	Mainly lower surface, 800/40 mm^{-2}, some with wax plugs; largely inactive on upper surface; epicuticular wax; pores also found on fruit 70 mm^{-2}	Cyclic oscillations, period of 20–40 mins; highest conductance 0900–1030 h, afterwards controlled by saturation deficit (>1.5 kPa); seasonal variation ?; linked to low air and soil temperatures	Stomata close at leaf water potential <–0.7 MPa at low saturation deficit or <–1.2 MPa at high value; midday minimum values –1.75 MPa irrigated, –2.3 MPa unirrigated	C_3 Light saturation occurs at about 25% full sunlight; cyclic oscillations (as with conductance)	Low stomata/canopy conductance restricts water use compared with other crops; rootstock can influence rate of sap flow in scion	Stem shrinkage	Limited evidence of osmotic adjustment when experiencing water stress
Coconut	Abaxial only 200 mm^{-2} talls >dwarfs?; Cl^- ions play important function	Stomata close as saturation deficit of the air increases; ‘dwarf’ cvs. stomata remain open longer than ‘talls’	Sensitive indicator of plant water status; reach –1.3 MPa when soil is wet, –2.0 MPa if dry; declines with increase in saturation deficit of air	C_3 Ceases at pre-dawn leaf water potential of –1.2 MPa; delayed recovery of photosynthesis after re-watering	Instantaneous WUE increased linearly with saturation deficit of air		Several, including rate of decline in leaf water potential in excised leaves; stomatal control of water loss; epicuticular wax; accumulation of organic solutes; ‘Talls’ more resistant than ‘dwarfs’; tolerates saline condtions

Date palm	Occur on both leaf surfaces in equal numbers; 160–180 mm^{-2}	Very little information; possible, wind-induced stomatal closure (>3m s^{-1}).	Very little information	May be closer to C_3 pathway than C_4 – needs confirmation.	$T = 0.5$ to 3.5 mm d^{-1}; time lag of 3 days between an irrigation event and an increase in T, but not with rainfall??	Thermal imaging???	Not known
Lychee	Abaxial only, also green fruit	Stomatal closure matches changes in leaf water potential; sensitive to saturation deficit of the air >2 kPa	Sensitive indicator of plant water status; should remain above –2.5 MPa	C_3 Maximum CO_2 assimilation occurs at PFD 500– 800 μmol m^{-2} s^{-1}, 27–32 °C and SD <0.7 kPa	No records	Relative leaf water content	Cell membrane stability?
Macadamia	Abaxial surface only; 360–500 mm^{-2}	Stomatal closure without concurrent changes in leaf water potential	In pot experiments virtually complete stomatal closure occurred at leaf water potential –1.8 to –2 MPa.	C_3 Diurnal changes in photosynthesis match changes in stomatal conductance; rates of photosynthesis depressed at temperatures >30 °C	Very efficient water transport system	Premature nut hardening	Not known

Table 13.3 *(cont.)*

Crop	Stomatal density	Conductance	Leaf water potential	Photosynthesis	Transpiration	Other indicators of plant water status	Drought resistance indicators
Mango	Abaxial only *c.* 400–700 mm^{-2}	Stomatal conductance declines gradually from *c.* 0900 h onwards Sensitive to saturation deficit of the air (0.5–4.0 kPa)	Latex exudation prevents pressure chamber giving reliable results	C_3 Photosynthesis closely correlated with conductance; also sensitive to saturation deficit, cv. dependent; photosynthesis rates less on leaves close to an inflorescence	In wet season, transpiration peaked in mid-afternoon before declining; transpiration measured with sap-flow method, also micro-meteorology		Cultivars may differ in their sensitivity to dry air
Olive	Abaxial surface only, 420–540 mm^{-2}; sunken below trichome layer, prevents dehydration	Conductance peaks early in morning, and then progressively declines; stomata close when evaporation rates are high	In well-watered trees leaf water potentials remain above –0.5MPa (pre-dawn) and –2.5 MPa (midday), and can reach –8 MPa when soil is dry	C_3 Rates of photosynthesis (and transpiration) follow similar diurnal trend to conductance; photosynthesis declines at temperatures >28–30 °C, zero at 40 °C	Positive linear relationship between sap flow and saturation deficit of air; transpiration peaks early afternoon and declines from 1600 h; recovery occurs within 7 d of re-watering; hydraulic conductivity of tree declines as summer progresses	Some measure of daily trunk shrinkage	Osmotic regulation and resistance to cavitation due to narrow xylem vessels; cultivars differ

Papaya	Abaxial surface only	Conductance is sensitive to saturation deficit of the air; stomata respond rapidly to changing light conditions	Not reported	C_3 Midday suppression of photosynthesis on clear days following partial stomatal closure; photosynthesis peaks at 35 °C	In morning, time lag in sap flow as water is taken first from storage in stem	None known	Cultivars appear to differ in certain physiological attributes
Passion fruit	Not reported	Small changes in leaf conductance for large change leaf water potential (pot experiment)	Not reported	Not reported	Not reported	Visual symptoms well documented	Chlorophyll *a* fluorescent transients?
Pineapple	Abaxial surface only, in troughs under trichomes; 70–85 mm^{-2} only, small size	Stomata open throughout the night, close during the day, reopening mid-afternoon (when well-watered)	Leaf tissue can store water; plants can prevent reverse flow of water from storage tissues into the soil	CAM Some reports 60–80% of CO_2 assimilation occurs at night, others $<3\%$	Averaged 2.3 to 2.5 mm d^{-1} in wet season, 0.6 to 1.0 mm d^{-1} in dry season	Relative thickness of so-called ‘D-leaves’	Not known, but it is a zerophyte

Rates of photosynthesis generally match levels in stomatal conductance, for example in *avocado*, *macadamia*, *mango*, *olive* and *papaya*. Low stomatal conductance restricts transpiration in *Citrus* when compared with other crops. Several drought resistance indicators have been identified, particularly for *coconut*. Genotypes of *avocado* and *olive* differ in the susceptibility of their xylem vessels to cavitation.

Water productivity

To increase crop yield per unit of scarce water requires both better cultivars and better agronomy. The challenge is to manage the crop or improve its genetic makeup to capture more of the water supply for use in transpiration; or to exchange transpired water for carbon dioxide more effectively in producing biomass and to convert more of the biomass into the harvestable product. (Passioura, 2004).

As competition for water increases world wide, so too does the need to quantify water productivity in yield and/or in financial terms in order to justify irrigated crop production. Many attempts have been made to measure water productivities in fruit orchards, but with limited success (Table 13.4). Despite the range of techniques available, there are still difficulties in quantifying crop water use with precision. In part this is due to seasonal variability and climate effects in the value of the crop coefficient (e.g., for *banana*, *Citrus*, *lychee*, *olive* and, perhaps, *coconut*).

These difficulties in estimating actual crop water use are further confounded by differences in crop management practices that impact on yield, as well as *ET*, and hence on water productivities. For example, the large number of cultivar/rootstock combinations that can exist within a species; the range of planting densities used (in some cases differing by a factor of over 20, e.g. *olive*); the training and pruning methods used to control vegetative growth and the soil surface management practices (e.g. bare (cultivated) soil, cover crop, mulch) employed. All of these variables influence actual crop water use, as well as the resultant yields. Biennial bearing also complicates the analysis (e.g. for *avocado*, *macadamia*, *mango* and *olive*), whilst relatively short-term experiments (two or three years) mean that longer-term cumulative benefits of irrigation are either not realised or are not taken into account.

For well-irrigated crops, the best estimates of the irrigation water productivities range from 1–2 (*avocado*), 2–3 (papaya), 3–5 (*mango*, *olive*), 5–6 (*pineapple*), 6–7 (*Citrus*) to 4–8 (*banana*) kg (fresh fruit) m^{-3}. For several of the fruit crops described (including *banana*, *cashew* (?), *lychee* and *mango*), dry air is a constraint to gas exchange, to dry matter production and ultimately to yield.

Deficit irrigation

The concept of *regulated deficit irrigation* was devised by researchers looking for ways to restrict excess vegetative growth in peach orchards (Fereres and Soriano, 2006). Savings in irrigation water were achieved in this way without a concomitant reduction in fruit yield or quality.

Table 13.4. Water productivity: summary table for 13 fruit crops.

Crop	ET_c	K_c	Limiting soil water deficit	Water productivity	Limiting factors	Deficit irrigation interval	Drought mitigation	Irrigation method	Other
Avocado	Peak rates in Mediterranean climates 3–5 mm d^{-1}	0.4–0.6	Soil should not dry, at depths of 0.30 m, below soil matric potentials of –30 kPa on sandy soils and –50 kPa on clayey soils	1–2 kg fresh fruit m^{-3} irrigation; limited information	Fruits in alternate years; sensitive to salinity; rootstocks vary; Mexican race more sensitive than Antillean	Water stress during flowering, fruit set and early fruit growth should be avoided	Mulch	Drip and undertree micro-sprinklers	Flooding can damage roots; rootstocks vary in sensitivity
Banana	Typical rates in the tropics 3–4 mm d^{-1}, up to 8 mm d^{-1} in summer elsewhere	No consensus in tropics; varies with growth stage; seasonal differences in subtropics 0.6 (winter) 1.0 E_{pan} (summer), and in Mediterranean climates	Soil water potential (Ψ_m) > -20 kPa at 0.2 m depth	Variable results; 40–80 kg fresh fruit ha^{-1} mm^{-1} (irrigation); yield response factor = 0.63 (?); quality criteria improved	Dry air restricts gas exchange	In subtropics 2–3 days only in summer	Mulch	Cooling of pseudostem by undertree sprinklers can delay development and reduce yields	Ratoon crop is ‘nomadic’
Cashew	Not recorded	Not recorded	Not recorded	Only/best estimate 0.26 kg (nut in shell) m^{-3} (irrigation water)	Dry air?	100 L tree-^{1} every 7–10 days during flowering; 200 L tree^{-1} every 15–20 days during fruit set (limited evidence)	Coconut husk burial; ‘modified crescent bund’	Drip and undertree micro-sprinklers	Variability between individual trees

Table 13.4. *(cont.)*

Crop	ET_c	K_c	Limiting soil water deficit	Water productivity	Limiting factors	Deficit irrigation interval	Drought mitigation	Irrigation method	Other
Citrus	Results very variable, summer range 3–8 mm d^{-1}; difficult to quantify	Very variable; changes with season; summer range 0.6–1.2	Maintain midday stem water potential above –1.3 MPa?; 0.4 depletion from flowering to fruit drop, afterwards 0.6–0.7	Fully irrigated crops 6–7 kg (fresh fruit) m^{-3} (water applied); partially irrigated 3–14 kg m^{-3}; not all comparisons are valid; fruit quality benefits	Our understanding of crop water requirements; short duration of experiments	No consensus view on degree of deficit irrigation likely to be of benefit to farmers		Drip and micro-sprinklers preferred	Stem shrinkage for scheduling?
Coconut	Direct comparisons difficult, range = 1.2– 7.8 mm d^{-1}; typical *c*. 3.0–3.5 mm d^{-1}.	Uncertain; perhaps seasonal variability; mature palms 0.5–1.02 × ET_o; working value 0.7 × ET_o	Not known	Full response only in third and subsequent years after irrigation begins; ball park yield response extra 20–40 nuts per palm	Causal links difficult to establish because of time delays	Not known	Husk burial; mulching; common salt	Basins, micro-sprinklers, drip	Can tolerate using seawater for irrigation
Date palm	Annual range 1000–2000 mm; seasonal range 0.5 to 5 mm d^{-1}; can reach 8–11 mm d^{-1}	Very variable: 0.6 up to 1.18; 'clothes line' and 'oasis' effects due to advection	Not known	Target 1.3 kg fresh fruit m^{-3} (water applied)	More sensitive to salinity than thought: E_{ci} <1.8 dS m^{-1}.	Not known	Subsurface drip irrigation; mulch	Flood, natural groundwater recommended; drip, micro-sprinklers, bubble.	Risk: groundwater depletion

Lychee	Not recorded; average c. 3–4 mm d^{-1}?	Limited work. 0.7–1.2 × ET_{pan}; K_c varies with ET_o?	Not known	Not known	Dry air in summer limits gas exchange; erratic flowering/fruit production	Irrigation intervals; 2–3 weeks sandy loam, 3–4 weeks clays	Mulching young trees; organic wastes including rice straw and dried grass	All methods, including 'boats' in Thailand; competition for water from summer rice crop	Balance between flower buds and vegetative buds governed by temperature
Macadamia	Best/only estimate 52 L d^{-1} $tree^{-1}$ (winter) 80 L d^{-1} (summer) Queensland	Not known	Not known	Not known; sensitive to water deficit at premature nut drop and nut maturation phases of growth	Nut yields are cyclical and highly variable: difficult to establish cause and effect	Not known; irrigation experiments inconclusive	Nothing specified		Moderately sensitive to salinity; relatively resistant to drought
Mango	Tropical, humid areas ET_c *c.* 4–5 mm d^{-1}, peak 5–6 mm d^{-1}	From 0.65 to 1.05, depending on frequency and extent of wetting of soil surface, and tree density	Not known.	For fully irrigated crops 3–5 kg fresh fruit m^{-3} (irrigation); for deficit irrigation 3–6 kg m^{-3}	Dry air closes stomata; biennial bearing; poor experimentation; range of tree densities	Not known	Nothing specified	Drip, micro-sprinklers preferred	Moderately sensitive/ moderately tolerant salinity; intensification issues
Olive	Total water use over a season 450–750 mm (*ET*) of which $T = 0.76\ ET$ with drip irrigation and $0.63\ ET$ with micro-sprinklers	Varies between 0.40 and 0.75, (assuming 50–60% crop cover), depending on season and whether arid or semi-arid	Not specified	Variable depending on amount of water applied; for applications of 100–150 mm productivity is about 3 kg fresh fruit m^{-3} (irrigation)	Variable tree densities not explained; biennial bearing; variable tree size; poor experimentation	No convincing evidence of any benefits from deficit irrigation or partial root-zone drying; deficit irrigation restricts vegetative growth, mixed messages on effects on oil quality	Nothing specified	Drip, micro-sprinklers preferred	Moderately tolerant of salinity; intensification issues; duplication of research effort Disease transmission in irrigation water

Table 13.4. *(cont.)*

Crop	ET_c	K_c	Limiting soil water deficit	Water productivity	Limiting factors	Deficit irrigation interval	Drought mitigation	Irrigation method	Other
Papaya	Few attempts made to measure *ET*	No reliable records	Not known	Limitations in design of experiments make it difficult to reconcile results; best estimates 1.8 to 2.8 kg fresh fruit m^{-3} irrigation water; increase in fruit size	Wind reduces *ET*	Not specified	Not specified	Drip and micro-sprinklers recommended	Sensitive to water-logging; moderately sensitive to salinity; responsive to irrigation
Passion fruit	One set of measurements; ET_c 3.5– 5.8 mm d^{-1}	No records	Not known	One crude estimate 2.5 kg fresh fruit m^{-3} irrigation	Seasonality of production; little research support	Not specified	Not specified	Drip and micro-sprinklers recommended (fertigation)	Beware damaging pollen during peak flowering with sprinkler irrigation, or irrigate at night
Pineapple	Few published reports on ET_c; for well-watered crop averaged 4 mm d^{-1} almost regardless of stage of development	*c.* 0.9 when well/ frequently watered	Not reported	Few published reports of field experiments; *c.* 5.6 kg fresh fruit m^{-3} (ET_c); 11 kg m^{-3} (*T*)	Lack of published information	Not specified	Not specified	Drip, micro-sprinklers, and traditional sprinklers	So little information, considering its importance and CAM attributes

According to Fereres and Soriano (2006), this observation has since been confirmed for many other fruit crops, including *almond*, *apple*, *pistachio*, *citrus*, *apricot*, *grapes* and *olive*. These researchers listed four reasons why deficit irrigation should be more successful in tree crops and vines than in field crops.

- The economic return from tree crops is often closely linked with the marketable crop yield.
- The yield-determining processes in fruit trees are not all equally sensitive to water deficits.
- It is possible to justify the extra cost of high frequency, micro-irrigation systems with fruit crops.
- Reductions in stomatal conductance at the level of the individual leaf have an immediate influence on the rate of transpiration from an aerodynamically rough crop canopy (i.e. scaling-up is possible).

In view of these statements it is surprising that very few of the experiments reviewed in this book have demonstrated convincingly the value of deficit irrigation in whatever form it was advocated or evaluated. This does not necessarily mean that it is not a concept worth pursuing. However, deficit irrigation has been used successfully in practice, which is the ultimate test for the value of any new practice. Very few *olive* orchards are now fully irrigated among the 0.5 million ha irrigated area in Spain. The same applies to wine *grapes* worldwide. It is likely that most of the species reviewed in this book are more sensitive to water deficits than those grown in subtropical/temperate areas. Fruit size may be an important factor when marketing crops like *avocado* and *mango* (Elias Fereres, personal communication).

Reporting research

The difficulty of undertaking and reporting research on fruit crops, which is highlighted in the quotation below, still holds good today:

> *It should surely be our aim as horticultural scientists to do the sort of experiments that can be thus interpreted, and used as the basis for valid extrapolation to other conditions i.e. to produce results that have some generalizing power; but this can only be achieved if our experiments are adequately designed and described. This is not a new concept, for instance 30 years ago Larson (1938) was emphasizing the need to take depth of soil, depth of roots, and water holding capacity of the soil into account when deciding how to irrigate apples. Yet few of the papers describing the results of research give the necessary information about these three factors, and fewer still give an adequate account of the meteorological conditions that determined potential evaporation rates during the work. There are no doubt special difficulties in experimenting with fruit trees, because of the slowness with which they fill the space, the uncertainty about where their absorbing roots are at any point of time and how densely they occupy the soil, and the constant conflict between vegetative growth and cropping, coupled with the two season cycle from bud formation to fruit ripening. As Goode (1970) has shown...effects of irrigation on growth may profoundly affect yield, but only after a delay of several seasons* (from Hudson, 1970).

All of the crops represented in this book are grown on different scales, from single plants/trees in a home garden (Figures 13.3 and 13.4) through small orchards/groves to large commercial orchards/estates/plantations. The priorities for research and its context also vary accordingly with the stakeholders. In some cases, experiments with similar objectives have been undertaken in several countries. This has resulted in some duplication of effort, especially with *olive*. To assist in identifying future research priorities, the main points that have emerged from the conclusions presented at the end of each chapter are summarised in Box 13.1.

Box 13.1 Summaries of the principal conclusions for each crop

Avocado

Despite the importance of avocado as an irrigated crop, its extreme sensitivity to waterlogging, and the diverse environments in which it is grown, there have only been a few attempts to measure its actual water use, and to quantify water productivity in systematic ways. Much of the research is empirical and lacks generic application. There has been only a limited amount of fundamental research on the water relations of avocado to assist in the extrapolation of results from one location to another. As growers rely increasingly on saline water for irrigation, so there is an increasing need to continue to identify cultivars with improved salinity tolerance. There is great variability in responses to water (and salinity) due to year-to-year variability, site-to-site differences, rootstock and scion interactions, and cultural practices, such as choice of plant population. This makes research on avocado particularly challenging! Unfortunately, much of the research reviewed here has been poorly reported, and the data are sometimes difficult to interpret. Of 60 references cited here on avocado, only a quarter were in refereed journals, whilst half had been published in ‘the grey literature’, as proceedings of conferences or as yearbooks, sometimes with limited quality control.

Banana

In the case of banana, a crop which is grown in relatively wet areas of the world, few experiments have been reported in which the aim was to identify at what stages in the development of the crop water applications can be reduced without a proportional loss in marketable yields. As Fereres and Soriano (2006) stated, research linking the physiological basis of these yield responses (generally well understood for the banana) to the design of practical ‘regulated deficit’ irrigation strategies could have a significant impact in water-limited areas (or where it is expensive to deliver water to the field). In addition, micro-irrigation systems can be used to control water applications and are therefore ideal for this form of stress management. Their design and operating criteria, usually the preserve of engineers, need to be specified with appropriate levels of precision (for specific farming systems) in order to maximise (marketable) crop water productivity, whilst minimising adverse effects on the water environment.

Cashew

Despite cashew having the reputation of being a drought-tolerant crop, water was expected to be one of the principal limiting factors. Research in both Brazil and Australia has focused on the limitations to productivity that climate, and water availability in particular, might impose. The capacity of mature trees to survive a long dry period prior to flowering, without loss of yield, has been largely established, as long as water is freely available from flowering to the start of harvest.

Continued

Box 13.1 (*cont.*)

The important role that the stomata play in maintaining a favourable leaf water status under dry (soil and air) conditions has been demonstrated, at least in part. However, reliable estimates of water productivity have yet to be established. This is partly because few (expensive) long-term field experiments have been undertaken. There is some evidence in Brazil that cultivars differ in their capacity to tolerate dry conditions/respond to irrigation. It can be expected that yield responses to water will vary with the tree density. There is a continuing need to develop a reliable method with which to estimate crop water requirements, to identify where and when irrigation of cashew is likely to be justified, and to develop a practical irrigation schedule. The requirements of the different farming systems within which cashew is a component will need to be considered. Cashew should not be allowed to remain as 'a poor man's crop and a rich man's food'. It is a very valuable, internationally traded commodity that can contribute to improved livelihoods for the many people who are involved in its production across the world. International cooperation on research would benefit everyone.

Citrus

Commercial production of *Citrus* spp. is concentrated in the subtropics, where irrigation is necessary, but where there is also great pressure to conserve water. Despite many recent attempts to specify how little water can be applied at specific growth stages to optimise water productivity, through 'regulated deficit' irrigation, no consensus view has emerged (the potential water savings may not be large). The effects of water availability on vegetative growth are understood in general terms, but the relationships have not yet been quantified. Similarly, the magnitude of the 'rest period' needed to induce flowering has not been specified with precision, nor have the effects of drought on flower and fruit formation, and fruit retention been quantified in useful ways. The diverse range of species, cultivars and rootstocks that exist within the *Citrus* spp. makes it difficult to draw generic conclusions. In contrast, environmental factors influencing stomatal conductances are generally well described and their relationships with some growth processes have been established. Progress has been made in quantifying crop water requirements under various conditions. The contribution of specific rootstocks to drought tolerance is worthy of study. Answers to the question, 'What proportion of the root zone needs to be irrigated?' are still needed. Formal evidence of the benefits to be obtained from irrigating several times a day – open hydroponics – is lacking.

Coconut

Until relatively recently much of the research reported was empirical, so that the results were only of value in the immediate location of the experiments. They were time and space limited. This is understandable and is due, in part, to the difficulty of undertaking research on this fascinating crop. Another factor is the limited funding available at the relatively small research institutes that have a mandate to undertake this research. There has also been, with some exceptions, a notable lack of international collaboration in research (coconuts are outside the CGIAR system) for a crop on which millions of people depend for their livelihoods.

Continued

Box 13.1 (*cont.*)

Date palm

Date palm production is concentrated in the Near East and North Africa region, where some 16 countries fall below the internationally accepted 'water-poverty limit'. These countries have rising populations demanding more water. Irrigated agriculture absorbs more than 80% of the available water resources that are also needed to facilitate economic growth, employment and food security. With very limited winter rainfall and depletion of the groundwater, most of these countries are increasingly dependent on the (expensive) desalination of seawater. Only high-value crops suited to the harsh environment with high water productivities can be justified as sustainable. The *date palm*, being indigenous to the region, meets these criteria, but local irrigation practices are inefficient. Adaptive research at the local level is needed to develop options to improve water productivity.

Lychee

Lychee is well established as an important fruit tree crop in South-east Asia, but has only relatively recently been introduced as a commercial crop elsewhere. Erratic flowering, and poor and variable fruit set affect orchards planted in many producing countries. Most of the research on tree physiology and water relations of this species has been conducted in South Africa and Australia.

Several studies have shown the importance of temperature on flowering, whereas water deficits have no direct effect on the process. Drought can be used to control shoot growth and hence flowering in areas that have dry periods during autumn or winter. Similar data suggest that moderate droughts after flowering can increase fruit production, although these gains are at the expense of fruit size. Severe droughts at this time reduce fruit set and yield, and can lead to fruit splitting. Well-grown trees on good soils can extract water down to 1.0 m or below. This reduces the need for frequent watering in commercial orchards. A watering every two to three weeks is probably sufficient for trees grown on sandy loams, and every three to four weeks on clays. Irrigation is best applied by monitoring changes in soil water levels. Further research is required to determine the benefits of irrigation in different growing areas, and the best way to apply the water.

Macadamia

Macadamia is unusual in that it is a crop where the centre of production is very close to its centre of origin (north-east Australia). This is also where most of the recent research on the physiology of macadamia has been undertaken. The main focus of this research has been to understand how temperature affects the growth of the nut, particularly the impact of high temperature on nut development and retention. Research has also been directed at how to manage a large self-shading tree so as to make best use of light, and to minimise premature nut shedding. The cyclical and highly variable nature of macadamia yields make this research difficult especially as it takes about 12 months from floral initiation to the completion of nut harvest. Macadamia can tolerate long dry seasons, so much so that mature trees appear to be unresponsive to supplementary irrigation. To demonstrate a yield response, experiments that last a minimum of five years are needed. It is arguable whether the experiments that have been reported so far have been sufficiently robust to answer the questions posed, namely, 'Where and when is irrigation justified?' and, 'What is the minimum quantity of water needed?' It is difficult to convince sponsors to

Continued

Box 13.1 (*cont.*)

fund research projects of that duration for a specialist (minor) crop, especially when the benefits are uncertain. But, if the potential of macadamia is to be fully exploited, this is what is needed.

Mango

Although the mechanisms responsible have yet to be fully explained, the flowering process in mango is now reasonably well understood. This includes the role of water in the initiation of flowering in the tropics. Similarly, some progress has been made in our understanding of the gas exchange processes, including stomatal (conductance and photosynthesis) responses to dry air. The sap-flow method has proved to be a useful way of measuring transpiration, and attempts have been made to monitor water use in mango orchards using a range of techniques. Unfortunately these experiments (and others) have not always been well reported. Although research has made some progress, the outputs are probably not something that the commercial grower would recognise as being immediately helpful. The big change in orchard management practices recently is the intensification of production, specifically increases in tree planting density. This will have a considerable impact on the water relations and irrigation requirements of mango, and should become the focus for future research.

Olive

After being grown as a subsistence crop for several thousand years in dry areas around the Mediterranean basin, the humble olive tree has suddenly become the centre of public attention. This renewed interest is a response, in part, to publicity about the health benefits associated with olive oil, which has increased demand. As a result, the crop is now being promoted and grown in countries away from the Mediterranean, in areas where the climate is different, in particular rainfall amount and distribution. This has led to fundamental changes in field agronomy, including increases in tree densities, the introduction of irrigation and the development of novel ways of training the tree in order to facilitate mechanical pruning and harvesting. This intensification has been supported by the contributions of international scientists who have not only evaluated the practical implications of these changes in traditional orchard management systems, but have also been able to obtain the resources needed to research the basic science, which is important for the longer-term future of the industry. A common theme has been the priority given by researchers (and their paymasters) to finding ways of minimising the amount of irrigation water needed, given the scarcity of water in many of the regions where olives are grown. The concept of ‘regulated deficit’ irrigation has been the subject of much research in several countries. Indeed it has become a fashion or ‘scientific bandwagon’ with the consequent duplication of effort.

Papaya

Although papaya is generally considered to be drought sensitive and responsive to irrigation, there is limited experimental evidence to support this view. Papaya is unusual amongst tree fruit crops in that it produces leaves, flowers and fruits on a continuous basis. Its productive life is also relatively short-lived. It should therefore be quite easy to establish cause and effect when developing relationships between water stress and yield. A uniform approach to irrigation experimentation and terminology would be a useful starting point. The sensitivity of the stomata

Continued

Box 13.1 (*cont.*)

to dry air is reasonably well established, but the actual water requirements have yet to be quantified with any precision. Unusually, a lot of effort has gone into explaining the effects of wind on the growth and development of papaya. Root systems are also well described. There is still a need to establish practical irrigation schedules for this remarkable crop.

Passion fruit

The review has highlighted at an international level the paucity of our scientific understanding of how passion fruit responds to its environment, in particular the role of water in its development and productivity. As an under-resourced, minority crop the way forward for the passion fruit industry should be through international cooperation on research topics of generic importance, including water.

Pineapple

There is little doubt that CAM plants such as pineapple can, in general, survive/tolerate dry conditions (details as yet unspecified) or areas with erratic rainfall. There is more uncertainty about the actual water use of pineapple, and relative rates of water loss (transpiration) and carbon gain (net photosynthesis), during the daytime and at night, under different water regimes. (This uncertainty is probably due to the capacity of the plant to shift from CAM to C_3 metabolism when water supply is adequate). This is surprising given the importance of pineapple as an internationally traded commodity and the amount of fundamental research reported on photosynthesis of CAM plants in general. So there is no agreed consensus in the literature on the values of the crop coefficient or on water productivity for pineapple. As a result, there is a lack of detailed advice to pineapple growers contemplating whether or not to invest in irrigation. Despite this lack of critical information, pineapple is still widely irrigated. This suggests that the large-scale private companies must have developed their own criteria for justifying and managing the irrigation of pineapples.

Research is usually prioritised where the need is greatest, where new crops are in demand and need to be evaluated, where the climate may be marginal, and, in the context of this book, where water stress is believed to be an important constraint, or where there happens to be an enthusiastic scientist. The most progress with respect to crop-water-related research is not necessarily made in the main production centres, but there are exceptions, such as *date palm* (research is underway in Saudi Arabia and Tunisia) and *macadamia* (fundamental research in Australia). In recent years, Brazil has been at the forefront of research on the water requirements of a large selection of crops, including *banana*, *cashew*, *coconut*, *mango*, *papaya*, *passion fruit* and *pineapple* (Figure 13.4). Similar research has been reported from South Africa and Australia on *avocado*, *banana*, *lychee* and *mango*.

Research priorities can change. For example, the USA once led the world with its research on *macadamia* (Hawai'i), *citrus* (California and Florida) and *papaya* (Guam),

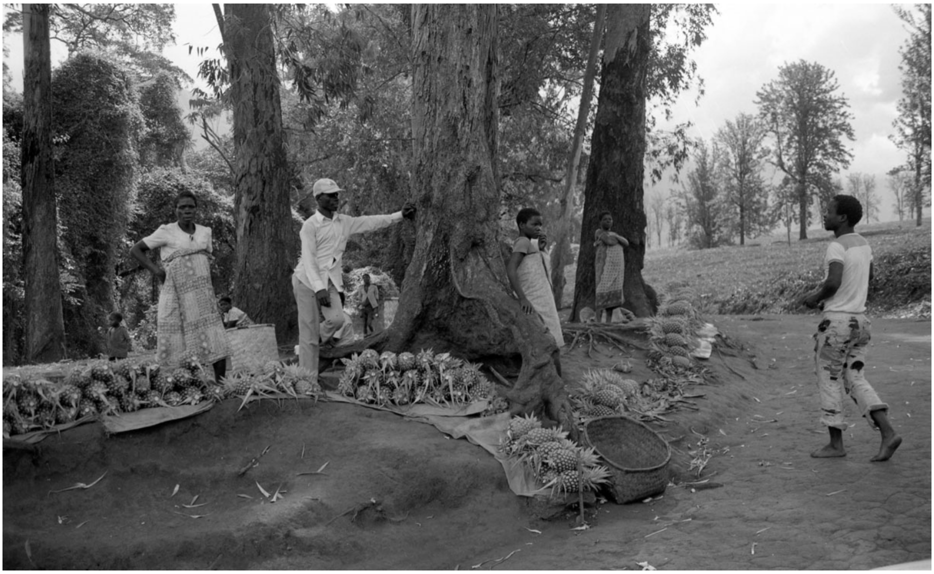

Figure 13.3 Much of the fruit produced by smallholders in the tropics is marketed and consumed locally. Here, pineapples are being sold at the side of the road in southern Malawi surrounded by tea and coffee plantations (MKVC).

Figure 13.4 Pineapples interplanted with coconut (BGD), irrigated with micro-sprinklers – Petrolina-PE, Brazil (LM). See also colour plates section.

but its international contribution appears to have declined in recent years. However *pineapple* has remained a priority crop in Hawai'i, *avocado* in California and *mango* in Florida. In Europe, Spain leads the way with research on *Citrus* and *olive* (as well as other Mediterranean-Basin crops).

The quality of reporting the outcomes from research in published papers is variable. Some of the publishers of journals have easy online access, whilst others expect a (substantial) payment for downloading individual papers. Access to publications by professional societies is particularly difficult (and expensive). The peer group refereeing procedures and editorial quality controls are sometimes inadequate. Research is not just about new discoveries. It is also about reviewing, re-interpreting and representing old information in ways that are relevant to today. For this reason, easy access to the literature through modern information retrieval systems is essential. We are entering a period of rapid change in the way research is reported.

Global challenges

Climate change

We are also entering, or more likely have already entered, a period of change in the world's climate. According to Corley (2012), the assumed association between the rise in atmospheric carbon dioxide levels over the last century, largely the result of man's activities, and the increase in global temperatures, is still open to doubt. Other factors may have contributed to warmer conditions. Agriculture, including tropical tree crops, will benefit from higher CO_2 concentrations. For example, biomass production and bunch yield from *oil palm* are both expected to increase, irrespective of the effects of a rise in temperature on, for example, respiration rates. The same applies to *coconut*, since the partitioning of assimilates is similar in pattern to that in *oil palm*. In addition, rising temperatures might even extend the latitude limits for *coconut*. In the case of *tea* grown at altitude in the tropics, any increase in temperature would increase yields, but in lowlands and subtropical regions higher temperatures (in the summer) might reduce yields. Rising CO_2 levels are not expected to influence yields of *tea*, since rates of photosynthesis are not the limiting factor. (The yield of *tea* is 'sink' limited, not 'source' limited). Corley (2012) does not claim that the Intergovernmental Panel for Climate Change (IPCC) projections are wrong, but simply that there are grounds for reasonable doubt.

Using 46 years of temperature records (1963–2009), Olesen (2011) established that winters in Alstonville, New South Wales, Australia (28.85° S 153.46° E; alt. 140 m) had been getting warmer (by 1.5 °C), but that summer temperatures were largely unchanged. Using temperature-based crop models, the impact of warmer winters on rates of flower and fruit development were predicted for several tree species. In this coastal region, the number of days between pruning in the autumn to the opening of the first flower in *custard apple* was now about 13 days less than it was. For *lychee*, the time taken for a single vegetative growth flush to be completed before the winter solstice was reduced by about ten days. For *macadamia* trees, the estimated time for the completion of one vegetative flush was now approximately 17 days shorter than before. By contrast, the time taken for the completion of a leaf flush in *macadamia* trees pruned in advance of the summer solstice (since the summer temperatures were largely unchanged) remained the same. In 2009, harvesting *mango* fruit was 12–16 days earlier compared with 1964 (cultivar dependent).

In an interesting study, Chaikiattiyos *et al.* (1994) compared the effects of temperature and water deficits on floral induction in four tropical fruit trees. For *avocado*, temperatures below 25 °C, and for *lychee* and *mango* less than 20 °C, were necessary for flowering to occur. These temperature requirements could not be replaced by water stress. In contrast, at day temperatures between 18 and 30 °C, flowering in *lemon* was mainly determined by water deficits. Warmer conditions during winter can be expected to promote more vegetative buds (and fewer flower buds) in *lychee* and *mango* in particular, but with little impact on flowering in lemon.

The commercial implications of any predicted changes will therefore vary with the species, whilst the debate about climate change and its implications to agriculture in the tropics (and elsewhere), and to the wider society, will continue for many years. The important thing is to recognise that climate change is happening, to plan future actions well in advance and to be prepared to adjust the way things are done. For example, with subtropical crops like *lychee* and *macadamia*, where vegetative growth occurs in a series of flushes, the timing of when to prune in relation to the flushing cycle (temperature dependent) is important, as pruning at the wrong time can result in poor flowering and accentuated fruit drop (Olesen, 2011).

Adopting change

Climate change also impacts on the need (or otherwise) for irrigation, on the availability of water, including the provision of storage facilities, and on how water is managed at the farm level (Figures 13.5 and 13.6) It is one thing to undertake and report research on irrigation water management. The really difficult bit is to encourage farmers to adapt and adopt new water management practices. It was for this reason that Boland *et al.* (2006) conducted a comprehensive three-stage study (between 1997 and 2000) of irrigation management practices, and farmers' willingness to consider change, in south-eastern Australia.

The first stage involved a detailed survey of 200 fruit (stone and pome) growers in four regions. Irrigation scheduling decisions were almost entirely based on experience (from 76 to >95% of the growers surveyed), although a significant proportion in two districts used tensiometers (19 and 28%) and a similar proportion (25% overall) used a shovel or an auger. There was no relationship between fruit yield and the amount of irrigation water applied, or between yield and the method of irrigation used: flood (practised by 30% of growers), percussion sprinklers (11%), micro-sprinklers (36%) and drip (23%). According to the authors, these observations indicated that growers were not motivated by the opportunities to improve water productivity, nor to apply water with greater precision than traditional methods allowed.

Figure 13.5 Fruit trees are grown as individual trees on irrigated homesteads such as this one in Swaziland (MKVC).

Figure 13.6 Water for irrigation is delivered to individual small farms from a diversion weir on a river through a network of small canals and control structures – Swaziland (MKVC).

The second stage was the development of an extension programme to promote the adoption by irrigators of best-management practices and the use of benchmarks. A monitoring programme, grower discussion groups, benchmarking (to enable growers to monitor their own performance) and demonstration sites (for example, of regulated deficit irrigation) were all set up in an area covering 40 orchards. At the end of this stage, there was a follow-up survey to determine any changes in irrigation management practices that had occurred as a result of the project.

The third stage was market research. This was designed to develop a better understanding of the key characteristics of those growers who embraced the need to adopt new technologies and practices. Following one-to-one interviews with 30 growers, a questionnaire was successfully distributed to about 740 growers and there was a 34% return of completed forms.

The lessons that emerged from this ambitious project will disappoint many researchers and others who think growers of fruit will be motivated by the desire to use water in a sustainable way, and to maximise water productivity by rational approaches to irrigation scheduling. The results showed that irrigation extension programmes should instead concentrate on other potential ancillary benefits such as labour saving, changes in production systems and marketing. To achieve voluntary adoption of sustainable irrigation practices on a large scale would require one-to-one extension services with targeted messages for specific groups (Boland *et al.*, 2006). Otherwise the desired outcomes could only be achieved by regulation and/or incentives. This would include, for example, a need to address public concern about the source of the food they eat, and to track it 'from farm to fork'. Supermarkets could provide the incentive (carrot or stick?).

The outcome of efforts such as those by Boland *et al.* (2006) are, however, site specific. For example, water availability and cost were not constraints in Boland's study area. There are other areas in the world where water scarcity is already forcing growers to practise deficit irrigation against their will. Examples include the Murcia Region of Spain and several areas of the Middle East. In such cases, the incentives to adopt advanced irrigation practices are directly related to water savings and increased water productivity (Elias Fereres, personal communication).

Training or education

In the 1980s a team of consultants was asked to address the issue of poor performance of irrigation projects, particularly in Africa (Carter *et al.*, 1986). The primary reason identified was the shortage of skilled manpower at all levels to plan and manage new irrigation schemes, despite the amount of money being spent on projects, and to manage existing projects. There were no procedures in place to assess on a continuing basis the number of people needed across a range of disciplines associated with irrigation (e.g. technicians, engineers, irrigation agronomists) and the level of expertise needed (e.g. vocational training, post-graduate education). Once this need had been assessed, it was then linked to the supply of suitably qualified people from existing in-country training and educational centres. In this way, any shortfall was identified and plans to address it could be made accordingly.

Figure 13.7 The California Aqueduct takes ‘blue water’ from the Sierra Nevada in the north of the state and delivers it to fruit farmers and other producers in the Central Valley and beyond (MKVC).

The needs of each country will differ according to the structure of its agricultural/horticultural industry, but the central message is the same regardless of location. Whether it is, for example, a private *kiwi fruit* farm in New Zealand, a large-scale smallholder scheme in Kenya producing *passion fruit* for export, a vineyard growing *grapes* for wine-making in Australia, a large commercial *Citrus* plantation in Florida, a *banana* estate in the Cameroon exporting to Europe, an *avocado* estate in California, a *date palm* plantation in Saudi Arabia, a *mango* orchard in India, or *pineapples* and *coconuts* (Figure 13.7) in Brazil, there is always a need for skilled people. Irrigation water management is an important and highly specialised activity embracing a number of diverse disciplines (as this book demonstrates), but we expect people to be able to do it well, in addition to their other farming activities, without any formal training or education. With (fresh) water becoming a scarce and expensive resource, and the need to protect the water environment from salinisation, and from nutrient and pesticide pollution, and with traceability becoming the norm, can we continue with this *laissez faire* approach? It would not be allowed in a factory producing jam, so why is it acceptable in the orchard where the fruit is grown?

The consultants recommended in their report on manpower planning (in Nigeria), amongst other things, the desirability of establishing, on an existing irrigation scheme or farm, a centre providing an exemplary demonstration of best practice in soil and water management, and associated irrigation project management skills. This demonstration centre would provide high-quality structured site experience for students at different levels and for those already in employment in agriculture. As far as it is known, such a centre has not yet been established anywhere, but the need is greater now than it was when the idea was first proposed by Carter *et al*. (1986).

Blue or green water

The debate about global water scarcity and food security has intensified in recent times (Figure 13.8). In addition, climate change is adding another layer of complexity by, for example, altering the temporal and spatial distribution of rainfall (Hanjra and Qureshi, 2010). Using the Global Crop Water Model (GCWM), Siebert and Döll (2010) have estimated that, over the period 1998–2002, about 6700 km^3 year of water was used annually by agriculture. Of this total 1200 km^3 was so-called *blue water*, namely water used for irrigation that was extracted from reservoirs, lakes, rivers and groundwater (Figure 13.9). The balance (known as *green water*), came from rainfall/precipitation falling on cropland, with 900 km^3 falling annually on irrigated crops and 4600 km^3 on rain-fed crops.

The GCWM predicted the blue and green water use of 26 classes of crop under rain-fed and irrigated conditions throughout the world. Included amongst these crops were three fruits (*date palm*, *citrus* and *grapes*), and several plantation crops (*sugar cane*, *cocoa*, *coffee* and *oil palm*). Although, by necessity, there were many assumptions made in the simulation (the limitations and uncertainties are discussed in the paper), the results for *citrus* and *date palm* are of particular interest here (Box 13.2).

Figure 13.8 Drought in the Murray–Darling Basin, Australia (MKVC).

Figure 13.9 Marketing fresh fruit is not always easy; to barter is the custom – Zimbabwe (MKVC).

Box 13.2 Blue and green water use by *citrus* and *date palm* (from Siebert and Döll, 2010)

Citrus:

- an estimated 48% of the total harvested area (75 000 km^2) is irrigated;
- the annual blue water use is 23 km^3 (which is equivalent to 57% of total water use by irrigated crops);
- green water use by irrigated *citrus* crops is estimated to be 17 km^3, and 29 km^3 by rain-fed *citrus* crops;
- blue water represents 33% of total water use by *citrus* worldwide.

Date palm:

- an estimated 79% of the total harvested area (9000 km^2) is irrigated;
- the annual blue water use is 11 km^3 (equivalent to 90% of the total);
- green water use by irrigated crops is 1.2 km^3, and 0.6 km^3 by rain-fed crops;
- blue water represents 85% of the total water use by *date palm* worldwide.

The vast majority (85%) of water used by *date palms* is blue water, reflecting the extent of irrigation in arid areas, and the access to groundwater surrounding oases. For *citrus* it is 33%, and for cocoa and coffee <0.05% and 1.1%, respectively. Taking all 26 classes of crop together consumptive use of blue water is less than 20% of the total (blue plus green). It is this 20% that would be available for re-distribution to other uses if irrigation was to be reduced.

As diets around the world improve (for example, more animal products are eaten, as well as more vegetables and fruit!), and as the world's population heads towards nine billion (by 2050) it has been estimated that an extra 5600 km^3 of water will be needed in agriculture, of which only 800 km^3 will come from blue water expansion (increased irrigation and improved efficiency). The remaining 4800 km^3 will have to come by bringing more rain-fed land into production, or by replacing evaporation by transpiration in order to improve water productivity by the crop (Hanjra and Qureshi, 2010).

Virtual water

International food trade also involves trade in water. This is known as the virtual flow of water from food producing and exporting countries to food importing and consuming countries, or virtual water trade. For example, to grow 500 t of fresh oranges for export requires 25 ha producing 20 t ha^{-1}. Say, for example, that 1500 mm of water is needed to produce this crop of oranges, of which 500 mm is 'blue water' (irrigation) and 1000 mm is 'green water' (rainfall). These figures, which apply to Florida and southern California, equate to $25 \times 10\,000 \times 0.5 = 125\,000$ m^3 blue water being exported and 250 000 m^3 of green water, a grand total of 375 000 m^3 or 375 000 tonnes of water (per year). By comparison, the mass of water exported in the fruit is only $500 \text{ t} \times 0.85 = 425$ t (*c*. 0.001% of the total).

Virtual water is a political issue. As the World Development Report (2010) states:

> *Virtual water may play an increasing role as water-rich countries export water embedded in food to water-short countries that find it increasingly difficult to grow sufficient staple food crops. But the aqua-politics of exporting/importing food versus self sufficiency will not be easy to resolve; food producing countries may not wish to export crops when food security is threatened; lower income and least developed countries may need to continue over-exploiting water resources to feed their populations.*

In times of water scarcity

In a comprehensive report on the way forward in terms of improving irrigation water management, prepared by Kay (2011) on behalf of the United Nations Conference on Trade and Development (UNCTAD), one of the key messages was that, in times of water scarcity:

> *Research must focus on the process of adaption and innovation rather than developing new technologies. Researchers must also focus more on uptake and dissemination of information and tailor it for different audiences including farmers, policy makers, extension services, schools and the general public.*

Following a review of irrigation on a global level, Turral *et al*. (2010) came to similar conclusions. Irrigation performance and agricultural water use must be further improved and targeted at higher-value enterprises (including fruit). As agriculture becomes more commercial and farm sizes expand, there will be increasing pressure on growers to make sound and economically rational investments. In extreme cases, irrigation projects

Figure 13.10 *Citrus* orchards abandoned in Arizona, USA because of a shortage of groundwater (MKVC).

Figure 13.11 The end product: a beautiful display of exotic fruit in a Chinese supermarket (MKVC).

may have to be abandoned as has happened in some parts of the USA where: (1) water and energy are cheap, (2) there is little or no restriction on the use of water and (3) the historical rights to water by land-owners has the same deep significance, in terms of personal liberty, as the right to carry a gun (Figure 13.10).

Concluding comment

Globally, irrigation will continue to play a fundamental role in food production, with increasing emphasis on the higher-value commodities, including fruit, since these are demanded by an increasingly affluent world (Figure 13.11). In times of water scarcity, there will be an ever-increasing need for irrigators to demonstrate that water is being used effectively. Research will continue to play an important role, but only providing that the research outputs are communicated clearly to the stakeholders, their uptake can be monitored, and their value to the industry and to the wider society can be clearly demonstrated.

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