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THE WATER RELATIONS AND IRRIGATION REQUIREMENTS OF LYCHEE (*LITCHI CHINENSIS* SONN.): A REVIEW

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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, 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.

INTRODUCTION

The cultivated lychee (litchi) is a rainforest species, which 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 19th century. The tree is grown for its clusters of small red fruit. 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

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S, at low altitude in the subtropics and (normally) at altitudes from 300–600 m in the tropics (Menzel and Simpson, 1994). 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 Organization 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, 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 paper is one of a series in which an attempt is made to collate information on the water relations and irrigation needs of fruit crops grown in tropical and subtropical regions. These crops include avocado, citrus and pineapple (Carr, 2012a, b; 2013). A similar series on plantation crops, including banana and coconut, has also been published as a book (Carr, 2012c).

The paper 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 flowers: 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' 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 predawn 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 occurred 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 the 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 six 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, 1994). 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 10-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, whilst 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 other two 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.

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. Predawn 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 (mid-summer), 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 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 (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), whilst 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. Predawn 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 0700–0800 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 recover rapidly (Jones, 1992).

Roe *et al.* (1995) also found that gas exchange in droughted trees took 10 days to return to pre-drought levels upon re-watering. They used a complex series of pot experiments to test if the results obtained from pot experiments 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 10–32 °C, before declining rapidly at higher temperatures. It declined exponentially as the saturation deficit increased from zero 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 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. 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 ($r^2 = 0.44$). The range of g_s values were similar in both examples.

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 that 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 chloropalsts 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 sunny 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. Predawn 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 μmol 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 m × 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 U.S. Weather Bureau Class A evaporation pan (E_{pan}) ranged from 20 to 70 mm week^{-1}. The crop coefficient ($K_c = ET_c/E_{pan}$) ranged from 0.4 to 1.2, with no seasonal trend. However, ET_c declined as E_{pan} increased, as shown by the following equation:

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

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 unusually high value, perhaps the result of local advection. 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 overestimates 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 PRODCTIVITY

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 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, which 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 related 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% ETc (rainfall only). Potential tree water use was calculated by multiplying evaporation from a U.S. Weather Bureau 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 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 0–50% × 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

The need for 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 deep 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. 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. 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, which 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 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 too much water was applied. The tree density was not stated.

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, historical estimates of crop evapotranspiration, constant application rates at 76 mm $week^{-1}$ during the experiment, or left unirrigated. The trees irrigated on the basis of crop evaporation received 71–73% 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, Australia and Israel.

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. 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 water.

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