

THE WATER RELATIONS AND IRRIGATION REQUIREMENTS OF PINEAPPLE (*Ananas comosus* var. *comosus*): A REVIEW

By M. K. V. CARR†

Emeritus Professor, School of Applied Sciences, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK

(Accepted 28 March 2012; First published online 15 May 2012)

SUMMARY

The results of research on the water relations and irrigation need 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 United States (Hawaii) 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 crop coefficient (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 rainfed 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, provided 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.

†Corresponding author. Email: mikedcarr@cwms.org.uk; Contact address: Pear Tree Cottage, Frog Lane, Ilmington, Shipston on Stour, Warwickshire CV36 4LQ, UK.

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 (Clement *et al.*, 2010; Duval *et al.*, 2003). After the ‘discovery’ of the New World in the late 15th century, pineapple spread rapidly throughout the tropics.

Pineapple is grown at low elevations at latitudes between 30° N (Assam, India) and 34° S (South Africa) (Malézieux *et al.*, 2003; Purseglove, 1972). 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). 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 (CO₂) at night. This dramatically improves its water-use efficiency when it is grown under dry conditions.

This paper attempts to synthesise research reported on the water relations of pineapple from an independent perspective, and to do this in practically useful ways. It follows the format used in previous reviews in this series, including plantation crops grown for their fruit, notably coffee (Carr, 2001), banana (Carr, 2009), coconut (Carr, 2011a), cocoa (Carr and Lockwood, 2011), oil palm (Carr, 2011b) and, most recently, *Citrus* spp. (Carr, 2012a). It 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 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 (Bartholomew 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 Hawaii, which was officially released in 1996, and is now the world's principal fresh-fruit-for-export cultivar (Bartholomew, 2009; PIP, 2011). 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 (for definitions, see below). A short, thick stem (that stores starch) supports 70–80 closely spaced succulent leaves. Water droplets (from rain and heavy 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 is 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 °C) 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 the prevailing temperature. Each inflorescence contains 100–200 flowers. 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 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.*, 2003a)

Fruiting

The parthenocarpic fruitlets that form fuse into a multiple fruit (known as a syncarp), the appearance of which is familiar to all. The cluster of small leaves that surmount the fruit is 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 Hawaii (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.

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.*, 2003a). 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) (Bartholomew and Kadzimin, 1977; Purseglove, 1972).

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 Hawaii (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 m 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 (Bartholomew *et al.*, 2003b; DPI, 2009). 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

Crassulacean Acid Metabolism (CAM)

In the context of promoting the potential of plants with 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 phosphoenolpyruvate carboxylase (PEPC)-mediated atmospheric and respiratory CO₂ 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 CO₂, which is fixed by the enzyme rubisco. As a result of CO₂ release into the intercellular spaces, stomata close in response to the elevated CO₂. In C₃ plants rubisco mediates the initial fixation of carbon. In C₄ 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 occur in the daylight. The temporal separation of C₄ and C₃ carboxylation underpins CAM. The closure of the stomata in the light and the concomitant, almost complete, cessation of transpiration (T) 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 C₃ and C₄ crops, but with only 20% of the water required for their cultivation (Borland *et al.*, 2009; Nobel, 1991).

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 CO₂ 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 CO₂ 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 (Borland *et al.*, 2009; Nobel, 1988).

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 mesophyll 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 CO₂ 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, CO₂ 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 C₃ species than a CAM species, as the C₄ 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 CO₂ assimilation that occurs at night is also affected by environmental factors such as temperature and CO₂ levels, although to a lesser extent. For example, values varied from 69 to 84%, depending on the day/night temperature regime (at ambient CO₂ levels), or from 63 to 68% at elevated CO₂ concentrations (Zhu *et al.*, 1999). Plants grown at elevated CO₂ levels had higher instantaneous water-use efficiencies than those grown at ambient levels, both when well-watered (c. +50%) or when subjected 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 C₄ plants (320 ± 43 g g⁻¹), 51 C₃ 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 ($70\text{--}85 \text{ mm}^{-2}$) and small size.
4. The stomata are open throughout the night, close during the day before reopening 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 that of C_4 plants and six times higher than that of C_3 species.

CROP WATER REQUIREMENTS AND WATER PRODUCTIVITY

In pioneering work in Hawaii, 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 United States Weather Bureau (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 Paraíba state in Brazil ($7^\circ 14' \text{ S}$ and $34^\circ 59' \text{ W}$; alt. 85 m), evapotranspiration from a pineapple crop (cv. Pérola) only occurred during daylight hours. (Azevedo *et al.*, 2007). These authors used the Bowen ratio method to monitor evapotranspiration 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 $4.1 \pm 0.6 \text{ mm d}^{-1}$ (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 ($=\text{ET}_c/\text{ET}_o$), 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 rewetting of the soil and crop surfaces by rain or irrigation water (although the authors do not mention this), rather than transpiration. The fresh fruit weight at harvest was 80 t ha^{-1} , giving a water productivity value, based on ET_c , of $5.6 \text{ kg (fresh fruit) m}^{-3}$. 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 CO_2 , water vapour and energy fluxes in a rainfed pineapple crop (cv. Red Spanish) over five consecutive wet/dry seasons in Venezuela ($9^\circ 38' \text{ N}$ and $63^\circ 37' \text{ W}$; 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 were $2.3\text{--}2.5 \text{ mm d}^{-1}$ in the wet seasons, falling to $0.6\text{--}1.0 \text{ mm d}^{-1}$ in the dry seasons, with a cumulative total (over 840 d) of 1725 mm (corresponding to $0.39 \times \text{USWB Class A pan evaporation}$). The proportion of the net daily dry matter production accumulated at night varied from zero 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 $1.0 \text{ kg carbon m}^{-3}$ for total dry matter production and $0.14 \text{ kg carbon m}^{-3}$ for fruit (equivalent to $11 \text{ kg fresh fruit m}^{-3}$).

Although Thorne (1953) was a pioneer in researching the role of irrigation (and trash mulch) in pineapple production in Hawaii, 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 have 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 Hawaii). 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 ET_c from pineapple is evaporation from the soil. The K_c mid < K_c ini since K_c mid occurs during full ground cover so that soil evaporation is less. For drip irrigation beneath plastic mulch the K_c 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 (Azevedo *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 evapotranspiration 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 rainfed 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), CO₂ 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 Hawaii 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 Hawaii, pineapple is grown in beds covered with plastic mulch to prevent the volatilization of nematicides injected into the soil to control plant-parasitic nematodes. Usually two rows of pineapple are planted into each sheet of plastic. 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 each bed beneath the plastic mulch, with one emitter supplying water to every two plants. According to Hawaiian 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 Hawaii, 2011). Herbicides that are broadcast over the whole area get washed off the plastic by rain and/or irrigation water from sprinklers and concentrated into the open and 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 Hawaii, 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 rainfed crop, it is widely irrigated, for example in Hawaii, and in Brazil where 20% of the cropped area is irrigated ($\equiv c.$ 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 as an internationally traded commodity and the amount of fundamental research reported on photosynthesis of CAM plants in general. There has been a similar lack of 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.

Acknowledgments. I thank Dr. D.P. Bartholomew for his helpful comments on a draft of this paper, and the two anonymous referees for their constructive analysis of the script.

REFERENCES

- Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. (1998). Crop evapotranspiration: guidelines for computing crop water requirements. *Food and Agricultural Organisation of the United Nations, Irrigation and Drainage Paper 56*, Rome, Italy.
- Almeida, O. A. de, Souza, L. F. da, Reinhardt, D. H. and Caldas, R. C. (2002). Influência da irrigação no ciclo do abacaxizeiro cv. Pérola em área de tabuleiro costeiro da Bahia. *Revista Brasileira Fruticultura* 24(2):431–435.
- Anderson, E. J., Carter, W., Ekern, P. C., Gowing, D. P., Klemmer, H. W., Radewald, J. D., Sakimura, K., Schmidt, C. T., Smith, D. H., Spiegelberg, C. H. and Tribble, R. T. (1961). *Establishing and Maintaining A Healthy Root System*. Research Report 86. Honolulu, HI: Pineapple Research Institute of Hawaii.
- Azevedo, P. V. de, Souza, C. B. de, Silva, B. B. da and Silva, V. P. R. da (2007). Water requirements of pineapple crop grown in a tropical environment. *Agricultural Water Management* 88:201–208.
- Bartholomew, D. P. (2009). 'MD-2' pineapple transforms the world's pineapple fresh fruit export industry. *Pineapple News* 16:2–5.
- Bartholomew, D. P. and Kadzimin, S. B. (1977). Pineapple. Chapter 5. In *Ecophysiology of Tropical Crops*, 113–156 (Eds P. de T. Alvim and T. T. Kozłowski). London: Academic Press.
- Bartholomew, D. P. and Malézieux, E. P. (1994). Pineapple. Chapter 11. In *Handbook of Environmental Physiology of Fruit Crops, Volume II Sub Tropical and Tropical Crops*, 243–291 (Eds B. Schaffer and P. C. Andersen). Boca Raton, FL: CRC Press.
- Bartholomew, D. P., Malézieux, E., Sanewski, G. M. and Sinclair, E. (2003a). Inflorescence and fruit development and yield. Chapter 8. In *The Pineapple, Botany, Production and Uses*, 167–202 (Eds D. P. Bartholomew, R. E. Pauli and K. G. Rohrbach). Wallingford, UK: CAB International.
- Bartholomew, D. P., Pauli, R. E. and Rohrbach, K. G. (Eds) (2003b). *The Pineapple: Botany, Production and Uses*. Wallingford, UK: CAB International.
- Borland, A. M., Griffiths, H., Hartwell, J. and Smith, J. A. C. (2009). Exploiting the potential of plants with crassulacean acid metabolism for bioenergy production on marginal lands. *Journal of Experimental Botany* 60(10):2879–2806.
- Carr, M. K. V. (2001). The water relations and irrigation requirements of coffee: a review. *Experimental Agriculture* 37:1–36.
- Carr, M. K. V. (2009). The water relations and irrigation requirements of banana (*Musa* spp.): a review. *Experimental Agriculture* 45:333–371.
- Carr, M. K. V. (2011a). The water relations and irrigation requirements of coconut (*Cocos nucifera* L.): a review. *Experimental Agriculture* 47:27–51.
- Carr, M. K. V. (2011b). The water relations and irrigation requirements of oil palm (*Elaeis guineensis* Jacq.): a review. *Experimental Agriculture* 47:629–652.
- Carr, M. K. V. (2012a). The water relations and irrigation requirements of *Citrus* spp.: a review. *Experimental Agriculture* doi:10.1017/S0014479712000385.
- Carr, M. K. V. (2012b). Sisal, Chapter 8. In *Advances in Irrigation Agronomy: Plantation Crops*, 187–194. Cambridge, UK: Cambridge University Press.

- Carr, M. K. V. and Lockwood, G. (2011). The water relations and irrigation requirements of cocoa (*Theobroma cacao* L.): a review. *Experimental Agriculture* 47:653–676.
- Chan, Y. K., Coppens d'Eeckenbrugge, G. and Sanewski, G. M. (2003). Breeding and variety improvement. Chapter 3. In *The Pineapple: Botany, Production and Uses*, 33–55 (Eds D. P. Bartholomew, R. E. Pauli and K. G. Rohrbach). Wallingford, UK: CAB International.
- Chapman, K. R., Glennie, J. D. and Paxton, B. (1983). Effect of five watering frequencies on growth and yield of various plant parts of container grown Queensland cayenne pineapples. *Queensland Journal of Agricultural and Animal Science* 40:75–81.
- Clement, C. R., Cristo-Araújo, M. D., d'Eeckenbrugge, G. C., Pereira, A. A. and Picanço-Rodrigues, D. (2010). Origin and domestication of native Amazonian crops. *Diversity* 2:72–106.
- Coppens d'Eeckenbrugge, G. and Leal, F. (2003). Morphology, anatomy and taxonomy. Chapter 2. In *The Pineapple, Botany, Production and Uses*, 13–32 (Eds D. P. Bartholomew, R. E. Pauli and K. G. Rohrbach). Wallingford, UK: CAB International.
- Cote, F. X., Folliot, M. and Andre, M. (1993). Photosynthetic crassulacean acid metabolism in pineapple: dual rhythm of CO₂ fixation, water use, and effect of water stress. *Acta Horticulturae* 334:113–130.
- De Souza, C. B., da Silva, B. B., de Azevedo, P. V. and da Silva, V. de P. R. (2008). Fluxos de energia e desenvolvimento da cultura do abacaxizeiro. *Revista Brasileira de Engenharia e Ambiental* 12(4):400–407.
- DPI (2009). http://www.dpi.qld.gov.au/documents/PlantIndustries_FruitAndVegetables/Ch1-The-Pineapple.pdf. [Accessed 4 December 2011].
- Doorenbos, J. and Kassam, A. H. (1979). Yield response to water. *Food and Agricultural Organisation of the United Nations, Irrigation and Drainage Paper 33*, Rome, Italy.
- Dubois, C., Fournier, P. and Soler, A. (2010). Growth indicators for Queen Victoria pineapple versus sum of temperatures, basis for a heat-unit model of vegetative growth. *Pineapple News* 17:15–18.
- Dusek, J., Ray, C., Alavi, G., Vogel, T. and Sanda, M. (2010). Effect of plastic mulch on water flow and herbicide transport in soil cultivated with pineapple crop: a modelling study. *Agricultural Water Management* 97:1637–1645.
- Duval, M. F., Buso, G. S. C., Ferreira, F. R., Noyer, J. L., Coppens d'Eeckenbrugge, G., Hamon, P. and Ferreira, M. E. (2003). Relationships in *Ananas* and other related genera using chloroplast DNA restriction site variation. *Genome* 46:990–1004.
- Ekern, P. C. (1964). *The Evapotranspiration of Pineapple in Hawaii*. Research Report 109. Honolulu, HI: Pineapple Research Institute of Hawaii.
- Ekern, P. C. (1965). Evapotranspiration of pineapple in Hawaii. *Plant Physiology* 40:736–739.
- Evans, D. O., Sanford, W. G. and Bartholomew, D. P. (2002). Growing pineapple. In *Pineapple Cultivation in Hawaii*, 4–8, (Eds D. P. Bartholomew, K. G. Rohrbach and D. O. Evans). Manoa, HI: Fruits and Nuts 7, Cooperative Extension Service, University of Hawaii.
- FAOSTAT (2011). <http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor>. [Accessed 7 July 2011].
- Hepton, A. (2003). Cultural system. Chapter 6. In *The Pineapple, Botany, Production and Uses*, 69–107. (Eds D. P. Bartholomew, R. E. Pauli and K. G. Rohrbach). Wallingford, UK: CAB International.
- Krauss, B. H. (1949). Anatomy of the vegetative organs of the pineapple, *Ananas comosus* (L.) Merr. II. The leaf. *Botanical Gazette* (Chicago) 110:333–404.
- Malézieux, E., Côte, F. and Bartholomew, D. P. (2003). Crop environment, plant growth and physiology. Chapter 5. In *The Pineapple, Botany, Production and Uses*, 69–107 (Eds D. P. Bartholomew, R. E. Pauli and K. G. Rohrbach). Wallingford, UK: CAB International.
- Malézieux, E., Zhang, J., Sinclair, E. and Bartholomew, D. P. (1994). Predicting pineapple harvest date in different environments, using a computer simulation model. *Agronomy Journal* 86:609–617.
- Matos, A. P. de and Reinhardt, D. H. (2009). Pineapple in Brazil: characteristics, research and perspectives. *Acta Horticulturae* 822:25–35.
- Nobel, P. S. (1988). *Environmental Biology of Agaves and Cacti*. Cambridge, UK: Cambridge University Press.
- Nobel, P. S. (1991). Achievable productivities of certain CAM plants: basis for high values compared with C3 and C4 plants. *New Phytologist* 119:183–205.
- Nose, A., Miyazato, K. and Murayama, S. (1981). Studies on dry matter production in pineapple plants. II. Effects of soil moisture on the gas exchange of pineapple plants. *Japanese Journal of Crop Science* 50(4):525–535.
- Nose, A., Shiroma, M., Miyazato, K. and Murayama, S. (1977). Studies on dry matter production in pineapple plants. I. Effects of light intensity in light period on CO₂ exchange and CO₂ balance of pineapple plants. *Japanese Journal of Crop Science* 46(4):580–587.

- PIP (2011). *MD2 Pineapple Variety Production Guide*. Brussels, Belgium: Pesticides Initiative Programme, COLEACP-UGPIP.
- Purselove, J. W. (1972). *Tropical Crops: Monocotyledons*. London: Longman.
- Ritchie, R. J. and Bunthawin, S. (2010). Photosynthesis in pineapple (*Ananas comosus comosus* [L.] Merr) measured using PAM (pulse amplitude modulation) fluorometry. *Tropical Plant Biology* 3(4):193–203 (published online 30 September 2010).
- San-José, J., Montes, R. and Nikonova, N. (2007a). Seasonal patterns of carbon dioxide, water vapour and energy fluxes in pineapple. *Agricultural and Forest Meteorology* 147:16–34.
- San-José, J., Montes, R. and Nikonova, N. (2007b). Diurnal patterns of carbon dioxide, water vapour and energy fluxes in pineapple (*Ananas comosus* (L.) Merr. cv. Red Spanish) field using eddy covariance. *Photosynthetica* 45:370–384.
- Silva, L. C. (2011). Fruit and vegetables production under irrigation in Brazil. Available online: <http://www2.mre.gov.br/aspa/semiario/.../Palestra%20Washington%20Silva.ppt> (accessed 9 August 2011).
- Souza, L. F. da S. and Reinhardt, D. H. (2007). Pineapple. Chapter 10. In *Tropical Fruits of Brazil*, 179–201 (Ed A. E. Johnston). Horgen, Switzerland: International Potash Institute (IPI, Bulletin 18).
- Stanhill, G. (1986). Water-use efficiency. *Advances in Agronomy* 39:53–85.
- Thorne, M. D. (1953). Report on irrigation and trash mulch experiments. *Pineapple Research Institute News* 1:64–70.
- Ting, I. P. (1985). Crassulacean acid metabolism. *Annual Review of Plant Physiology* 36:595–622.
- University of Hawaii (2011). <http://www.ctahr.hawaii.edu/fb/pineappl/pineappl.htm#Irrigation> (accessed 9 August 2011).
- Zhu, J., Bartholomew, D. P. and Goldstein, G. (2005). Photosynthetic gas exchange and water relations during drought in ‘Smooth Cayenne’ pineapple (*Ananas comosus* (L.) Merr.) grown under ambient and elevated CO₂ and three day/night temperatures. *Acta Horticulturae* 666:161–173.
- Zhu, J., Goldstein, G. and Bartholomew, D. P. (1999). Gas exchange and carbon isotope composition of *Ananas comosus* in response to elevated CO₂ and temperature. *Plant Cell and Environment* 22:999–1007.