

THE WATER RELATIONS AND IRRIGATION REQUIREMENTS OF COCOA (*THEOBROMA CACAO* L.): A REVIEW

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SUMMARY

The results of research into the water relations of cocoa are reviewed in the context of drought mitigation and irrigation need. Background information on the centres of production of the cocoa tree, and the role of water in crop development and growth processes, is followed by reviews of the effects of water stress on stomatal conductance, leaf water status and gas exchange, together with drought tolerance, crop water use and water productivity. Leaf and shoot growth occur in a series of flushes, which are synchronized by the start of the rains following a dry season (or an increase in temperature), alternating with periods of 'dormancy'. Flowering is inhibited by water stress but synchronous flowering occurs soon after the dry season ends. Roots too grow in a rhythmic pattern similar to that of leaf flushes. Roots can reach depths of 1.5–2.0 m, but with a mass of roots in the top 0.2–0.4 m, and spread laterally >5 m from the stem. Stomata open in low light intensities and remain fully open in full sunlight in well-watered plants. Partial stomatal closure begins at a leaf water potential of about -1.5 MPa. Stomatal conductance is sensitive to dry air, declining as the saturation deficit increases from about 1.0 up to 3.5 kPa. Net photosynthesis and transpiration both consequently decline over a similar range of values. Little has been published on the actual water use of cocoa in the field. Measured E_{Tc} values equate to <2 mm d^{-1} only, whereas computed E_{Tc} rates of 3–6 mm d^{-1} in the rains and <2 mm d^{-1} in the dry season have also been reported. Despite its sensitivity to water stress, there is too a paucity of reliable, field-based published data of practical value on the yield responses of cocoa to drought or to irrigation. With the threat of climate change leading to less, or more erratic, rainfall in the tropics, uncertainty in yield forecasting as a result of water stress will increase. Social, technical and economic issues influencing the research agenda are discussed.

INTRODUCTION

The cocoa tree (*Theobroma cacao*) is cultivated in the humid tropics for its seed (bean), the vast majority of which is used in the food industry for the production of chocolate and powder (for drinking, baking and ice cream manufacture). A small proportion is also sold as cocoa butter, which is used in the pharmaceutical and cosmetic industries. Cocoa is of international importance as a smallholder crop (5–6 million farmers) with only about 5% (our best estimate) of the world crop (annual total = 3.6 million t) produced on plantations. Historically, most cocoa was planted in newly thinned forest with little investment of monetary capital during the establishment or maintenance phases (Ruf, 1995). Nowadays, little forest remains in the traditional growing areas and

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its conversion to cocoa is not acceptable. Replanting former cocoa land is costlier and, as it is usually lower yielding, it is less profitable. In West Africa, where cocoa is usually grown under shade, there are long-standing problems over the tenure of the cocoa trees and shared cropping is widespread. As an internationally traded commodity, cocoa contributes to the livelihoods of an estimated 40–50 million people (World Cocoa Foundation, 2010).

A great deal of research has been reported on the ecophysiology and water relations of cocoa and this paper attempts to synthesize this research from an independent perspective and to do this in practically useful ways. It follows the format used in previous reviews in this series notably on coffee (Carr, 2001), banana (Carr, 2009), tea (2010a; 2010b), sugar cane (Carr and Knox, 2011) and coconut (Carr, 2011). It begins with a summary of the origin and centres of production of cocoa and the stages of crop development (including roots) in relation to water availability, followed by reviews of plant water relations, crop water use and water productivity. Various aspects of this topic have previously been reviewed (e.g. Alvim, 1977; Balasimha, 1999; Fordham, 1972) including, most recently, a paper by Almeida and Valle (2007) with a focus on factors influencing the growth and development of the cocoa tree. Emphasis here is placed on those publications describing research which has international relevance.

CENTRES OF PRODUCTION

The centre of diversity of cocoa is believed to be within the rainforests of lowland northern South America where the greatest range of variation in natural populations exists (Cheesman, 1944; Simmonds, 1998). In its natural habitat cocoa is a small tree in the lower storey of the evergreen rain-forest. Cocoa has been cultivated since ancient times (at least 2000 years) in Central America, from Mexico to southern Costa Rica. After the arrival of the Spaniards in the 16th century, cocoa spread rapidly in the New World. It was introduced into southeast Asia in the 17th century and to West Africa in the 19th century. The plant develops fruits known as cocoa pods (botanically an indehiscent drupe). The pods contain seeds, which are fermented with the mucilage surrounding them and then dried to give fermented dried cocoa, the raw material used to make chocolate (Wood, 1985b).

By 2008, the total planted area of cocoa in the world was estimated to be about 8.6 million ha of which 67% is in West Africa and only 17% in the Americas and the Caribbean. It is nearly all grown within 20°N and 20°S of the equator (World Cocoa Foundation, 2010). The largest individual producer is Côte d'Ivoire (1.22 million tonnes; 2.3 million ha in 2008), followed by Ghana (662 000 t; 1.75 million ha), Indonesia (490 000 t; 990 000 ha), Nigeria (250 000 t; 1.15 million ha), Cameroon (227 000 t; 500 000 ha) and Brazil (157 000 t; 641 000 ha). (Areas harvested from FAO, 2010; production from ICCO, 2010). West Africa now produces 69% of the world's annual total of 3.6 million tonnes of cocoa. The market value of the cocoa crop is US\$5.1 billion (World Cocoa Foundation, 2010).

The climates of the major cocoa growing countries have been described by Wood (1985a). The average annual rainfall totals range from 1300 mm (Gagnoa, Côte

d'Ivoire) to 2800 mm (Keravat, Papua New Guinea), but it is not the total alone that matters but rather the distribution of rain through the year. In Malaysia (Perak, 4°N) and Papua New Guinea (Keravat, 4°S) rainfall is uniformly distributed, but in Ecuador (Pichilingue, 1°S) and South India (8–10°N), for example, there is a single, long dry season. In West Africa (5–8°N) there are generally two dry, or less wet, seasons. Only a very small proportion (*ca.* 0.5%) of the area planted with cocoa is thought to be irrigated.

In a comprehensive analysis of growth processes of cocoa in different regions of the world, Hardy (1958) identified the following critical air temperatures for commercial cocoa production: the mean annual temperature should not be <22 °C, the mean daily minimum not <15 °C, and the absolute minimum not <10 °C.

Types

Traditionally, cocoa was classified according to trade perceptions of its physical and sensory quality and associated botanical traits, albeit imperfectly (Cheesman, 1944).

- *Criollo*: cultivated on a small scale because of its lack of vigour, although the area is currently expanding due to renewed interest in speciality cocoa.
- *Forastero*: the bulk of the world's cocoa production is from this type.
- *Trinitario*: usually considered to be the result of crosses between the other two types and is not found in the wild. Material designated as Trinitario is grown commercially in the Caribbean and Papua New Guinea.

Recently, Motamayor *et al.* (2008) have proposed a new classification of cocoa germplasm. Based on an analysis of over 1000 individual trees from different geographic areas within the Amazon basin, and using microsatellite markers, they identified 10 genetic groups or clusters, rather than the three listed above, namely: Marañon, Curaray, Criollo, Iquitos, Nanay, Contamana, Amelonado, Purús, Nacional and Guiana. The authors believe that this new classification reflects more accurately the genetic diversity available to breeders.

Traditionally, cocoa has always been propagated from seed although the potential for clones (with a *plagiotropic* – at an angle to the vertical – growth habit, see below) has long been recognized (Lockwood and Boamah Adomako, 2010). The breeding and adoption of new seedling cultivars has led to large increases in productivity, for example in Ghana (Edwin and Masters, 2005).

CROP DEVELOPMENT

Cocoa seedlings exhibit two growth forms: a vertical (*orthotropic*) stem, known as a *chupon*, with spiral phyllotaxi, together with three to five lateral (*plagiotropic*) fan branches ($\frac{5}{8}$ phyllotaxi). The point from which the buds grow out sideways from the terminal end of the main stem is known as a *lorquette*. Clones propagated from *chupon* buddings have the same growth habit as seedlings, whilst material propagated from fan buds has the same morphology, growth and flowering habit as fan branches (and very rarely produce an *orthotropic* shoot).

The phenological growth stages of cocoa plants have been described in detail by Niemenak *et al.* (2009) using the 'extended BBCH-scale'. In summary, development can be divided into the following principal growth stages:

Growth stage 0: seed germination–vegetative propagation. Growth stage 1: leaf development on the main (vertical) stem, and on the fan branches. Growth stage 2: main stem elongation, formation of a *jorquette* of fan branches and another *chupon*. Growth stage 3: fan branch elongation. Growth stage 5: inflorescence emergence. Growth stage 6: flowering. Growth stage 7: development of fruit. Growth stage 8: ripening of fruit and seed. Growth stage 9: senescence. (Note, growth stage 4 does not apply to cocoa only to cereals.)

These growth stages are further subdivided into secondary and tertiary growth stages. For the purposes of this review we are principally concerned with the development of the leaf canopy (growth stages 1–3), flowering (growth stages 5–6) and fruit development and ripening (growth stages 7–8).

Stem and leaf canopy development

Leaf development occurs on the main stem (*orthotropic*) as well as on the fan (*plagiotropic*) branches. Initially about 10 leaves begin to develop and expand at the same time. This is known as a leaf flush (Greenwood and Posnette, 1950). After about 40 days a second (and third and so on) flush occurs. As this rhythmic process is largely independent of climate it is considered to be under endogenous control (Almeida and Valle, 2007). Leaves differ in appearance depending on the type of stem on which they arise (the petioles are about 60 mm longer on *chupons*, allowing the leaf to be orientated in relation to the light) (Burle, 1961).

An individual shoot passes through alternate periods of growth and 'dormancy', during which leaf primordia/small leaves are developing in the apical bud (Hardwick *et al.*, 1988a), and follows a similar pattern to the leaf flush cycle (Greathouse *et al.*, 1971). The growth period is characterized by the expansion of leaves and elongation of the shoot. During dormancy the length of the shoot remains constant and no new leaves expand. The main stem reaches physiological maturity after one or two years from planting (at a height of 1.0–1.2 m) when the apical meristem stops growing and a *jorquette* of *plagiotropic* branches (3–5) begin to develop, and these in turn eventually branch. At the same time a second vertical stem (*second chupon*) appears on the main stem (*first chupon*). In the course of time, a second whorl of fan branches develops. This process may be repeated several times such that the canopy increases in height (up to 10 m when cultivated and even 20 m when uncultivated and under heavy shade). This is customary practice in West Africa. Cocoa may be pruned to limit its height to 3–5 m, when only the initial *jorquette* and subsequent branching growth are retained, further *chupons* are continually removed to restrict the eventual vertical growth, and fan branches may be pruned in order to develop an efficient plant structure and for cultural management.

The importance of light interception and distribution within the canopy in limiting productivity in cocoa germplasm was highlighted by a field study in Malaysia (Yapp and Hadley, 1994). For cocoa with a full canopy (48 months after transplanting),

planted at a conventional density (1096 trees ha⁻¹), precocity and yield were a simple function of intercepted radiation (f). In a comparison of 12 genotypes, there were large variations in the value of ' f ' (from 0.50 to 0.82), and in the bean yield/intercepted radiation conversion efficiency (0.085–0.133 g MJ⁻¹). In contrast, for cocoa planted at high density (3333 ha⁻¹), with full canopy cover, yield was related to light distribution in the canopy and the degree of attenuation represented by the light extinction coefficient (k). Shaded leaves low in the canopy can contribute more to dry matter production when the value of ' k ' is small (Hadley and Yapp, 1993). The effect of the age of a leaf and its position within a canopy on its productivity (rates of photosynthesis and respiration) has been described by Miyaji *et al.* (1997).

Subsequently, the importance of canopy structure in cocoa was confirmed by Daymond *et al.* (2002a). In a comparison of 10 clones in Brazil, the leaf area index (L), for example, reached values ranging from 2.8 to 4.5 (plants spaced 3 m square). There were associated differences in the relationship between L and the fractional light interception. In addition, clones also vary in the base temperature for main stem growth ranging, for example, from 18.6 °C (AMAZ 15/15) to 20.8 °C (SPEC 54/1) (Daymond and Hadley, 2004). For comparison, the minimum duration of a leaf flush cycle occurs at a daily mean air temperature of about 26 °C (Hadley *et al.*, 1994).

Based on the results of a large trial in Sabah, Malaysia, Lockwood and Pang (1996) concluded that the optimum plant density can vary between clones (the densities compared were 1096 and 3333 plants ha⁻¹). Later, Pang (2006) confirmed that, at the current stage of cocoa breeding, selection for adaptation to planting density was of higher priority than selection for yield efficiency (the ratio of cumulative yield over a period of time to the increment in the cross-sectional area of the trunk over the same time period).

Drought symptoms: water availability, by influencing the rate of canopy expansion, and hence light interception, can be expected to influence the productivity of young cocoa. When droughted, seedlings quickly reach a 'point of no return' from which they can not recover. Visible symptoms of drought include premature leaf fall (progressively younger leaves abscise), the yellowing of basal leaves, wilting, small leaves and slow trunk growth. The relief of water stress is followed by a large, synchronized flush of leaf growth (Hutcheon, 1977b), but the flushing cycle that follows is independent of plant water status (at least until the next dry season) (Hardwick *et al.*, 1988b). Synchronized leaf growth can also be triggered by an increase in temperature (Hutcheon, 1981a).

Flowering

Flowers form in meristematic tissues located above leaf scars on the main stem and woody branches (*cauliflorus*). Seedling trees do not flower until after the second flush has hardened on *jourquette* branches, but plants budded from *plagiotropic* growth can flower when the second growth flush has hardened. An individual site (commonly known as a 'cushion', or strictly as a 'compressed cincinnal cyme' (Purseglove, 1968), can have flowers at different stages of development whilst up to 120 000 flowers can be produced

each year on a single tree. The floral meristem produces flowers over the tree's entire life span. There is marked seasonal variation in flower production (Edwards, 1973). Flower opening is synchronized and the anthers release their pollen early in the morning. Various small insects, including midges (*Ceratopogonidae: Forcipomyia*), are responsible for pollination. Unfertilized flowers abscise from the stem about 24–36 h after anthesis. Only 0.5–5% of flowers develop into mature pods.

In Ghana, Smith (1964) found that irrigation of young cocoa increased growth rates, advanced flowering and increased the number of flowers (in the second year after planting) but did not affect the percentage of fruit set compared with the unirrigated control treatment. In his rainfall-only treatment, flushing (leaf production) within a population was synchronized by the onset of the rains, whilst in the irrigated treatments trees responded as individuals. Sale (1970a) found that each time potted cocoa plants were watered following drought, vigorous flushing (and flowering) occurred, beginning about 10 days after watering. Similarly, field observations in Brazil indicated that after a period of water stress, during which flowering was inhibited, had ended with the start of the rains, synchronous flushing (and flowering) occurred (Alvim and Alvim, 1977). By transferring plants from low (50–60%) or medium (70–80%) relative humidity to high humidity (90–95%), Sale (1970b) was able to show that flowering could also be induced by the relief from atmospheric-induced water stress. These and other factors influencing seasonal periodicity of flushing and flowering in Ghana have been described by Hutcheon (1977b).

Fruit development

From anthesis to the maturation of the fruit takes 150 days or more. In Papua New Guinea, Bridgland (1953) reported actual total gestation periods (recorded in a progeny trial) lasting from 163 to 200 days (mean 182). These were similar durations to those found later in the Cameroon (between 167 and 200 days) (Braudeau, 1969). The fruit remains attached to the tree until harvested. There are two critical points during the development of the small fruits (known as *cherelles*) when they may stop growing (known as 'cherelle wilt'). The first, at about 40 days after fertilization of the flowers, coincides with the first division of the fertilized egg. The second, after about 75 days, coincides with greatly increased fat and starch metabolism and the onset of rapid growth of the fruits (McKelvie, 1956). At either susceptible stage, more of the *cherelles*, even all of them, may wilt if the tree is flushing heavily. However, if the tree is not flushing and all the *cherelles* are at the same developmental stage following synchronized manual pollination, few if any wilt and if the crop is large, flushing is suppressed. If, when the pods are harvested, replacements are set by synchronized manual pollination of freshly opened flowers, they develop normally, without wilting. The trees do not flush, and they may die back.

When fruit set is not synchronized artificially, cherelle wilt is considered to be a fruit thinning mechanism, which occurs in response to a limited carbohydrate supply and competition between pods for carbohydrates, whereby younger pods are preferentially 'wilted'. In this respect, water stress has an indirect impact on the 'wilting' process as

carbohydrate assimilation is reduced. Whether water stress also has a direct impact on another growth process such as, for example, cell division in the *cherelle* is not known. Rather than being a yield-limiting factor itself, *cherelle* wilt therefore reflects any carbohydrate limitation to pod growth. The number of seeds per fruit is normally in the range 20–50. The rate of increase in pod dry weight is slow for the first 60 days after pollination and peaks after about 100 days before declining.

The timing of harvests varies from region to region depending on temperature and rainfall distribution (Alvim, 1988). For example, in the state of Bahia, Brazil (14°S), where there is no clearly defined dry season, low mean air temperatures (<23 °C) in June, July and August restrict flowering, which results in low yields seven months later. In warmer locations, harvests are mainly influenced by rainfall distribution, again with a six to seven month delay between cause (the start of the rains) and effect (mature fruit).

Genotypes differ in the sensitivity of fruit growth to changes in air temperature, which can affect time to fruit ripening, fruit losses from *cherelle* wilt, final pod size, bean size and lipid content (Daymond and Hadley, 2008). There are also differences between cultivars in the base temperature for fruit growth (range: 7.5 °C for genotypes Amelonado and AMAZ 15/15 to 12.9 °C for SPEC 54/1).

Potential yield

The potential annual biomass (above ground) productivity of cocoa was estimated by Corley (1983) to be 56 t ha⁻¹. Based on an assumed harvest index of 0.20 (perhaps an over-estimate) the maximum seed yield was predicted to be 11 t ha⁻¹. This is considerably more than the best recorded yield of 4.4 t ha⁻¹ (without shade) and the best commercial yields of 1.5–2.5 t ha⁻¹ (Joe Thau-Yin Pang and G. Lockwood, personal communication). Limiting factors, in addition to water stress and pests and diseases, included shade trees (limiting photosynthesis; competition for water), excessive leaf temperatures (especially when grown without shade), low air temperatures (e.g. in Bahia, Brazil), and foliage susceptible to wind damage (benefits from shelter, but reduced leaf cooling because of less wind).

Daymond *et al.* (2002a; 2002b) have confirmed the potential for yield improvement in cocoa by selectively breeding for efficient partitioning of biomass to the yield component. In a field experiment in Bahia, Brazil, they found, over an 18-month period, a seven-fold difference in dry bean yield between the 12 genotypes tested, ranging from the equivalent of 200 to 1400 kg ha⁻¹. During the same interval, the increase in trunk cross-sectional area ranged from 11.1 cm² to 27.6 cm², with yield efficiencies varying between 0.008 kg cm⁻² and 0.08 kg cm⁻². Of the seven clones compared, beans accounted for between 32% and 45% of the pod biomass.

Roots

According to Kummerow *et al.* (1981), summarizing the work of others, cocoa seedlings are characterized by a fast growing tap root on which are formed a limited number of rootlets. After three or four months a first ring of lateral roots has been

established. These grow vigorously always close to the soil surface (<100 mm depth) and branch at their distal parts into dense clusters of fine roots. After four to six years these laterals have spread 4–6 m from the stem forming a mat of fine roots, which extend into the decomposing litter layer. Based on detailed measurements in Brazil, Kummerow *et al.* (1981) estimated the total length of these roots for an 11-year-old cocoa tree to be 1200 m m⁻² or the equivalent of 1.2 m² of root surface for every 1 m² soil surface. The tap root continues to grow in thickness and length reaching depths of 1.0–1.5 m depending on soil conditions. Lateral roots develop on the tap root at depth, some of which grow upwards. By combining fine root production with reasonable estimates of the dry mass of other roots, including the tap root, the total dry mass of roots was estimated to be conservatively 10 t ha⁻¹.

Similar descriptions of the root systems of cocoa have been provided by Wood (1985a) and Toxopeus (1985). Both refer to the detailed work in Trinidad summarized by McCreary *et al.* (1943), whilst Van Himme (1959) has described with illustrations the results of a major study of the root system of cocoa in the Democratic Republic of Congo. The proportion by dry mass of the tap root to the total root system was found by Thong and Ng (1980) on an inland soil in Malaysia to be constant at 0.84 almost independent of the plant age (up to seven years). By contrast, in a similar study but this time on a coastal clay soil where a water table limited the development of the root system, the tap root represented only 0.15–0.30 of the total dry mass of the root system (Teoh *et al.*, 1986).

By observing roots in a glass-sided box, filled with soil, Vogel (1975), working in the Cameroon, found that roots of cocoa seedlings grew in length in a rhythmic pattern having the same period as the leaf flush. The greatest root growth rate occurred *before and during* each flush. Subsequently, Sleigh *et al.* (1981), using a similar method in the UK, confirmed the cyclic nature of root extension, but with maximum root development *alternating* with active leaf expansion. By contrast, Taylor and Hadley (1988), also in the UK, found that periods of rapid root growth *coincided* (within three or four days) with maximum rates of shoot growth (and *vice versa*). During the periods between successive leaf flushes, root growth continued but at a reduced rate. These observations were made in a controlled environment greenhouse with a nutrient film system.

Roots of cocoa appear to grow in a rhythmic pattern but its timing in relation to a leaf flush is uncertain (possibly this is a result of the different methods of root measurement used). There are practical implications in terms of the sensitivity of cocoa to water stress at different stages in the flush cycle, or the best time to transplant seedlings to the field, and subjects worthy of further research.

In a remarkably detailed experiment, Moser *et al.* (2010) simulated an *El Niño* drought in Central Sulawesi, Indonesia (1.55°S, 120.02°E; alt. 585 m) by reducing rain reaching the soil by 70–80% (with plastic roofs placed beneath the cocoa canopy) for 13 months in a six-year-old cocoa plantation. The cocoa was shaded by *Gliricidia sepium*. All aspects of dry matter production were monitored, including roots, relative to the unprotected control area. Excavations before the drought revealed a superficial distribution of roots in the profile with >83% of the fine roots (<2 mm diameter)

and >86% of coarse roots (2–50 mm), both by dry mass, being found in the top 0.40 m. There were significant quantities of fine roots to a depth of 1.0 m whilst the deepest were found at 2.0 m. Coarse roots extended to 1.5 m. Surprisingly, there were no differences in root distribution or mass between the control and the sheltered cocoa at the end of the drought 13 months later. A few roots extended laterally up to >1.0 m, although coarse and large roots (2–150 mm) were concentrated within 0.5 m of the stem. The roots of *Gliricidia* penetrated much deeper than those of cocoa with considerable numbers of fine roots present at 2.5 m depth.

Little work appears to have been done on genotypic variation in root:shoot ratios.

Summary: crop development

1. Cocoa has a dimorphic growth habit.
2. Flushes of leaf and shoot growth, synchronized by the commencement of the rains after a dry season (or an increase in temperature), alternate with periods of 'dormancy'.
3. Light interception by the leaf canopy, and light distribution within the canopy, are important determinants of yield.
4. Visible symptoms of drought include premature leaf fall (progressively younger leaves abscise), the yellowing of basal leaves, wilting, small leaves and slow trunk growth.
5. Flowering is inhibited during periods of water stress (and by low temperatures) but the start of the rains results in synchronous flowering.
6. Water stress during fruit development results in small pods and may be an indirect contributory factor in cherelle wilt.
7. Roots grow in a rhythmic pattern but there is conflicting evidence of its timing in relation to shoot growth flushes.
8. Although cocoa is considered to be shallow rooting, roots can extend to depths of 1.5–2.0 m. A large proportion of the roots (80%) are located in the top 0.2–0.4 m.
9. Roots can extend laterally considerable distances (>5 m), but the majority are within 0.5 m of the stem.
10. Only a few of these processes have been quantified in practically useful ways.

PLANT WATER RELATIONS

Stomata

Stomatal size and frequency as well as the structure and distribution of leaf waxes of two seedling cocoa varieties (Catongo and Catongo/SIAL) were described by Gomes and Kozłowski (1988). In a greenhouse study in Wisconsin, USA, the average density of stomata, which are found only on the abaxial (lower) surface of the leaf, was about 700 mm^{-2} . Both leaf surfaces were covered with heavy deposits of amorphous wax, except for near the stomatal pores. By comparison, in Malaysia, stomatal densities in mixed hybrid seedlings averaged 820 mm^{-2} in irrigated seedlings but 1110 mm^{-2}

in unirrigated plants (increase in density associated with smaller leaves) (Huan *et al.*, 1986). In a comparison of eight contrasting genotypes in a greenhouse environment in the UK, Daymond *et al.* (2009) recorded stomatal densities ranging from 788 to 1081 mm⁻² (mean 960). In contrast, the densities recorded by Balasimha *et al.* (1985) in a comparison of 40 accessions in South India averaged only about 100 mm⁻² (range 80–122). Such a low density compared with other research suggests an error in measurement or in reporting.

In pioneering research, Alvim (1958) used the infiltration technique to monitor the degree of stomatal opening in cocoa, and showed, with cuttings and young plants, that the method could be used as a practical indicator of water stress in cocoa. In a field study with five-year-old plants, which were not suffering from water stress, stomatal opening increased as the light intensity increased with maximum opening in strong sunlight.

Using a diffusion porometer in Ghana, Hutcheon (1977a) found that stomatal conductance was controlled mainly by the leaf water status. Partial stomatal opening at low light intensities is a feature of shade-tolerant species like cocoa, as is the capacity of the stomata to respond quickly to changing light intensity. The stomata of well-watered field-grown cocoa plants generally remained open in full sunlight.

Leaf water status

In a review of early research on the water relations of cocoa, Fordham (1972) emphasised the importance of recording the internal water status of a plant if the results of research on crop water use were to have application at sites away from where the research was undertaken. Attempts to relate rainfall amount and distribution to yields in Ghana, Nigeria and Trinidad had, for example, merely emphasized that the relationships are not simple and have little generic value. Similarly, attempts to quantify the role of irrigation in crop productivity in Ghana and Trinidad had failed to establish causal relationships as they did not always take into account either the influence of pore size distribution on soil water availability, or the impact of the aerial environment (e.g. effects of solar radiation/shade, humidity and wind) on evaporative demand at the crop surface. Since preliminary results had been encouraging, Fordham (1972) advocated the use of the pressure chamber technique for determining the water status of field-grown cocoa plants, a method subsequently confirmed, in a comparative test, as being suitable for cocoa by Yegappan and Mainstone (1981) in Malaysia.

In Ghana, Hutcheon (1977b) described the sequential changes in leaf water potential (and its components) as water stress increased, as recorded in a diverse range of experiments. Initially in a wet soil, values were high early in the morning, declining to about -1.2 MPa by the middle of the day before recovering in the afternoon. As the soil dried midday values declined, reaching lows of -1.5 MPa when midday stomatal closure restricted further water loss. As the soil dried out, recovery from midday closure became weaker until leaf water potentials remained low even at night. There was no evidence of diurnal changes in osmotic potential but some evidence of considerable seasonal changes (down to -2.4 MPa).

In Ecuador, by contrast, low evaporation rates, due to dull, cool conditions, at the start of the long (six months) dry season prevented the midday leaf water potential, measured in the upper canopy of unirrigated, shaded 12-year old trees, from declining below that recorded in irrigated trees (about -0.8 MPa) until there had been 3–4 months without rain. By the end of the dry season, the leaf water potential had reached -1.6 MPa. There was no similar reduction in stomatal conductance which remained relatively constant throughout the dry season. Osmotic adjustment may have occurred. Similar measurements made in semi-arid north-east Brazil, where irrigation is also necessary and where evaporation rates are higher than in Ecuador, indicated how drought stress occurred earlier in the dry season (leaf water potential reached -1.4 MPa within two months) with a large differential in stomatal conductance between irrigated and unirrigated trees (Orchard, 1985).

Gas exchange

In Ghana, Hutcheon (1977a) found a close relationship between photosynthesis rate (measured with the $^{14}\text{CO}_2$ method on a wide range of cocoa genotypes and growing conditions) and stomatal conductance, indicating that stomata are an important controlling factor in photosynthesis. Stomata are sensitive to the dryness of the air. For example, in a greenhouse experiment in the UK (under low light conditions), stomatal conductance fell (cv. West African Amelonado) when the saturation deficit of the air exceeded about 1.0 kPa, and continued to decline over the range tested (up to 3.0 kPa). Rates of photosynthesis (measured with an infra red gas analyser) also declined over the same range of values. In contrast, transpiration at first increased with the saturation deficit but, at values above 1.0 kPa, remained constant (Raja Harun and Hardwick, 1988). In another greenhouse experiment, this time in Indiana, USA, Joly (1988) judged that net photosynthesis of seedlings declined once the leaf water potential fell below about -0.8 to -1.0 MPa. The relationship (with pooled data) between net photosynthesis and stomatal conductance was again (Hutcheon, 1977a) best described by an exponential asymptotic equation. Assimilation rates varied linearly with transpiration. The three cultivars tested (EET399 and EET400, half siblings of Ecuadorian Oriente origin, and one Trinitario type, UF613) differed in their instantaneous water-use efficiencies, that is net photosynthesis divided by transpiration (Joly and Hahn, 1989).

By contrast, in a greenhouse/controlled environment study in Maryland, USA, three different genotypes (CCN 51, LCT EEN 37/A and VB 1117 representing different types) responded in similar ways to changes in ambient conditions (light intensity, carbon dioxide concentration and dryness of the air). As an example, the short-term effects of increasing the saturation deficit of the air (from 0.9 to 2.2 kPa) were to reduce the rate of net photosynthesis slightly, to increase transpiration but to have minimal effect on stomatal conductance. Cocoa was considered to be unusually ineffective in limiting transpiration in dry air compared with other rain forest tree species (Baligar *et al.*, 2008).

The sensitivity of the stomata of cocoa to the saturation deficit of the air was demonstrated further in Colombia by Hernandez *et al.* (1989). Stomatal conductance declined rapidly in shaded plants (*cv.* ICA4xIMC67) as the saturation deficit was increased from 0.5 to 3.5 kPa, whilst apparent carbon dioxide uptake was reduced at values above about 2.0 kPa. Transpiration at first increased as the saturation deficit was increased from 0.5 to 1.0 kPa, but then declined, reaching very low values at 4.0 kPa. The implications of these observations to the sustainable management of cocoa under field conditions were considered, in particular the value of shade (water use efficiencies are likely to be higher under shade, although in practice this will depend on such things as the amount of light intercepted by the shade canopy, the leaf area index of the cocoa canopy and the ambient light conditions) and irrigation (responses will be limited during periods of hot, dry air).

In a field study in India, Balasimha *et al.* (1991) also found that photosynthesis declined as the saturation deficit of the air increased above about 2 kPa. Drought tolerant accessions maintained higher leaf water potentials during dry months than drought susceptible ones.

In Malaysia, container-grown plants were subjected to water stress of different durations. Leaf water potentials fell to minimum values of about -3.0 MPa in droughted plants with a suggestion that the critical value below which stomatal conductance and photosynthesis both declined was about -1.5 MPa. There was an indication that one genotype (KKM25) could withstand water stress better than the other two (KKM4, KKM5) tested (Razi *et al.*, 1992).

A similar study was undertaken in a semi-arid region of Venezuela ($08^{\circ}31'N$ $71^{\circ}71'W$; alt. 1100 m) this time with field-grown, shaded, four-year-old plants (*cv.* Guasare, Criollo type) irrigated every 3, 12 or 25 days. Minimum leaf water potentials were in the range -1.4 to -1.7 MPa, and there was evidence of osmotic adjustment, but only in the 3- and 12-day treatments. In severely stressed plants, daily photosynthesis was reduced by 25% and transpiration by 39% compared with the 3-day treatment, which implies an increase in water-use efficiency (Rada *et al.*, 2005). In a greenhouse experiment in the UK, significant differences in the instantaneous water-use efficiencies were recorded in the eight genotypes compared, ranging from 3.1 (IMC47) to 4.2 mmol mol^{-1} water (ICS1) (Daymond *et al.*, 2009).

Shading, as well as water, also influences gas exchange processes. In a nursery experiment in Ghana, young clonal plants were shaded with netting at three different levels (32.5, 55 and 76% shade). The plants were kept well watered. During the two rainy seasons, stomatal conductance, photosynthesis and transpiration all declined as the level of shade increased, but during the dry season the situation was reversed (Acheampong *et al.* 2009). This difference between the seasons was explained by the dryness of the air. Saturation deficits averaged about 1.4 kPa in the rains and 2.7 kPa in the dry season.

That wind can physically damage cocoa was confirmed in a wind tunnel experiment in Wisconsin, USA. Of particular interest though was the observation that an increase in wind speed from 1.5–3.0 m s^{-1} to 6.0 m s^{-1} increased stomatal conductance, but *reduced* transpiration. This was apparently the result of a reduction in the leaf:air

saturation deficit associated with cooling of the leaves by the wind (Gomes and Kozlowski, 1989).

Drought tolerance

In South India, where there is an extended dry season, Balasimha *et al.* (1988) developed a procedure for determining the relative drought tolerance of cocoa accessions. Based on an assessment of a number of plant parameters, including effective stomatal control of transpiration when under water stress, five accessions (NC23, NC29, NC31, NC39 and NC42) were identified as being drought tolerant. Later, Balasimha *et al.* (1999) evaluated the drought tolerance of the progeny of crosses between four high yielding and three drought-tolerant pollen parents (NC23/43, NC29/66, and NC42/94). Using the rapid excised leaf screening method (based on changes in leaf water potential of an excised leaf in 90 minutes (Balasimha and Daniel, 1988)), and follow-up field measurements during the dry season over a five-year period, they identified two hybrids (1-21 \times NC42/94; 1-29 \times NC23/43) exhibiting drought tolerance characteristics on the basis of their higher leaf water potentials and stomatal resistances during dry weather.

In a comparison of eight clones (all grafted on to local Comum variety rootstocks) in a greenhouse experiment in South Bahia, Brazil, three were identified as being drought tolerant on the basis of the degree of osmotic adjustment recorded, but only when dehydration was imposed rapidly (Almeida *et al.*, 2001). The osmotic adjustment was associated with the accumulation of potassium and phosphorus ions in the leaf. These three clones (SPA5, SIAL70 and TSH516) were recommended for growing on drought prone shallow soils in the region. By contrast, Premachandra and Joly (1994) could find no evidence of osmotic adjustment in cocoa seedlings subjected to water stress over a 22-day period in a glasshouse experiment in Indiana, USA.

According to Bae *et al.* (2008), it may be possible to enhance drought tolerance in cocoa by altering polyamine levels, which are associated with the response of plants to drought, either by selection or by genetic manipulation. Although transgenic techniques in cocoa are at present discouraged because of consumer concerns, the genes involved in polyamine biosynthesis have been identified.

Bae *et al.* (2009) have also identified another possible way of enhancing drought tolerance in cocoa. They found that colonization of young cocoa seedlings by the endophytic fungus *Trichoderma hamatum* (isolate DIS 219b) promoted growth and delayed the onset of drought symptoms through changes in gene expression. The primary direct effect of colonization was to promote root growth (dry weight and fresh weight) regardless of the plant water status. This delayed drought-induced changes in stomatal conductance, net photosynthesis and green fluorescence emissions as well as wilting.

Summary: plant water relations

1. Stomata are found on the abaxial surface of the leaf at densities of 700–1100 mm⁻².

2. Stomata open in low light intensities and remain fully open in full sunlight on well-watered plants.
3. Leaf water potentials in well-watered plants can decline to -1.2 MPa at midday, before recovering.
4. As the soil dries, minimum values of leaf water potential can reach -3.0 MPa in droughted plants.
5. Partial stomatal closure begins at a leaf water potential of about -1.5 MPa.
6. Stomatal conductance is sensitive to dry air, declining as the saturation deficit increases from about 1.0 up to 3.5 kPa.
7. Net photosynthesis declines over a similar range of values.
8. Transpiration initially increases but when the saturation deficit exceeds about 1.0 kPa it begins to decline (or remains constant), reaching very low values at 4 kPa.
9. Cultivars differ in their instantaneous water-use efficiencies.
10. Leaf water potential and stomatal conductance measurements have been used to identify drought resistant cultivars.
11. There is conflicting evidence about the contribution of osmotic adjustment to drought tolerance.

CROP WATER REQUIREMENTS

Few attempts have been made to quantify the actual water use of cocoa in the field. In Côte d'Ivoire, Jadin *et al.* (1976) used a neutron probe to monitor changes in the soil water profile beneath young cocoa plants irrigated with sprinklers or with drip. Using a similar set of measurements, Jadin and Snoeck (1981) developed linear relations between actual water use for irrigated and unirrigated crops and a Penman equation (date unspecified) estimate of evapotranspiration, and also between water-use and evaporation from a pan (Colorado). It is not easy to apply these findings with confidence elsewhere.

Based on the Penman-Monteith equation (Allen *et al.*, 1998), and using published values of the key parameters (including crop, aerodynamic and surface resistances) controlling transpiration and evaporation from crop and soil surfaces, Radersma and Ridder (1996) computed evapotranspiration by cocoa (and three other crops) for La Mé, Côte d'Ivoire (*ca.* $5^{\circ}20'N$ $4^{\circ}02'W$; alt. 35 m). Assuming an annual rainfall total of 1500 mm, daily transpiration rates (T) were estimated to be between 3.0 and 6.1 mm d^{-1} during the rains, depending on net radiation levels and the saturation deficit of the air, and from 1.0 to 1.9 mm d^{-1} during the dry season. The corresponding seasonal and annual totals for evapotranspiration (ET_c) were 584 mm (wet season), 294 mm (dry season) and 878 mm (total).

The sap-flow technique was used by Colas *et al.* (1999) in Indonesia ($40^{\circ}38'S$ $105^{\circ}15'E$) to measure transpiration of individual cocoa trees (eight years old) grown alone (1333 ha^{-1}) or in association with coconut (1186 and 87 trees ha^{-1} respectively). On dry days, transpiration increased rapidly early in the morning, reaching maximum values of $2.5\text{--}3.0 \text{ l dm}^{-2} \text{ h}^{-1}$ before declining from about 11:00 hours onwards, when

the saturation deficit of the air reached about 2 kPa, as a result of stomatal closure. On wet days, transpiration rates remained relatively constant during the middle of the day. Over a consecutive 18-day period, transpiration averaged the equivalent of about 1.31 mm d^{-1} , (or $10 \text{ l tree}^{-1} \text{ d}^{-1}$) compared with a Penman (1948 version) potential ETo estimate of $3\text{--}5 \text{ mm d}^{-1}$. This equates to a crop factor (Kc) value of about 0.3 (see below). For comparison, transpiration by cocoa in the crop combination averaged 1.19 mm d^{-1} .

In the simulated *El Niño* drought experiment reported by Moser *et al.* (2010) in Central Sulawesi, Indonesia (described above under *Roots*), the combined average rate of water use by both species, cocoa and *Gliricidia sepium*, (as measured with heat dissipation sap flux sensors) was only 1.3 mm d^{-1} in the protected plots and 1.5 mm d^{-1} in the control (70% of which was from the cocoa trees), values similar to those reported above, but still surprisingly low (Kohler *et al.*, 2010). Drainage represented 55% of the annual rainfall in the control plots and 11% in the protected plots.

Water requirements (ETc) derived from estimates of potential evapotranspiration by a reference crop (ETo) require a crop factor ($Kc = ETc/ETo$). Allen *et al.* (1998) suggested a Kc value of 1.0–1.05 for a cocoa crop with a complete canopy. The Kc value is based on a theoretical understanding of the processes of transpiration and evaporation from a tall crop, and assumes full crop cover or frequent wetting of the soil surface. The evidence on evapotranspiration presented above suggests this Kc value is too high, but it depends on the actual crop cover in the two field experiments described.

Summary: crop water requirements

1. Little has been reported on the water use of cocoa.
2. Field data (based on the sap flow method) suggest ETc rates of $<2 \text{ mm d}^{-1}$ which, for a crop with a complete canopy, would appear to be low.
3. The corresponding Kc value is only 0.3, much less than the theoretical value for a cocoa crop or any crop with complete ground cover.

WATER PRODUCTIVITY

Yield forecasting

A number of attempts have been made to relate cocoa yields to rainfall, for example in Trinidad (Dunlop, 1925), Papua New Guinea (Bridgland, 1953), Ghana (Ali, 1969; Maidment, 1928; Skidmore, 1929) and Nigeria (Toxopeus and Wessel, 1970), also reviewed by Fordham (1972). But, as the role of rainfall in crop growth is not a simple one, these attempts have had limited success. Recently, a physiological growth and production model for cocoa has been developed and described by Zuidema *et al.* (2005). Known as SUCROS-Cocoa, it is based on the SUCROS-family of models with parameter values taken from the literature. It simulates biomass production and bean yield for different situations and locations. Lack of good independent data has limited the validation of the model. Regression analysis showed that over 70% of the

variation in simulated bean yield could be explained by a combination of annual solar radiation and rainfall in the two driest months. Yield losses due to drought of up to 50% depending on location and soil type were predicted. Heavy shading (>60%) reduced yields by more than 30%. Opportunities to improve the model were identified.

Responses to irrigation

In view of the apparent sensitivity of cocoa to drought, there have been surprisingly few irrigation experiments, but perhaps less surprising given the limited likelihood of commercial scale irrigation. Murray (1961) reported the results of one such experiment in Trinidad, but problems in applying and monitoring the amount of water applied in the dry season (acknowledged by the author) meant that the results obtained over five years (no consistent yield advantage from irrigation) had little value. Low atmospheric humidity in the dry season was suggested as a possible limiting factor. An irrigation experiment in Ghana was also compromised by poor design (recognized as a weakness) that meant the data could not be analysed statistically. Yield increases of 12, 17 and 40% were obtained from mature Amelonado trees by keeping the soil close to field capacity in the three years 1960–1962. These increases were less than anticipated at the time due, it was again thought, to ‘dry air’ constraints. No absolute yields were presented (Hutcheon *et al.*, 1973).

Another irrigation experiment was undertaken in Malawi (16°31'S 35°10'E; alt. 52 m) by Lee (1975). The depth of water applied was based on three evaporation pan factors (0.6, 0.8 and 1.00 × Epan (Kenya type)), with two irrigation intervals based on calculated soil water deficits (52 or 104 mm). Detailed records were kept for two years (1971/72 and 1972/73) when the average annual rainfall was 710 mm and the depths of water applied over the long dry season were 920–1650 mm. Yields of wet beans from a 4–5 year-old Amazon cultivar (T76) were similar for all three water applications, averaging about 2200 kg ha⁻¹. More frequent irrigation out-yielded less frequent irrigation by 285 kg ha⁻¹ (2318 and 2032 kg ha⁻¹), although plot to plot variability was large (CV > 30%). Hot dry winds damaged the crop towards the end of the dry season. The alluvial soil had a water holding capacity of 230 mm m⁻¹. The seasonality of harvest was not affected by any of the treatments.

In Côte d'Ivoire, Jadin and Jacquemart (1978) compared two methods of irrigation (sprinklers and drip) with an unirrigated control treatment on the development and yield of young cocoa over a two-year period. Sprinkler irrigation was applied when the measured soil water deficit reached 20 mm, whilst drip irrigation was applied when the soil water tension reached 20 kPa at 0.20 m depth. As a result in part of these differences in scheduling irrigation, considerably more water was applied with the sprinklers in the dry season (535 mm) than with drip (224 mm). Irrigation, particularly drip, speeded up the rate of development, increased the number of flowers, and increased yields but did not affect the periodicity of the growth cycle.

The results of an unreplicated field scale irrigation trial in Peninsular Malaysia were later reported by Huan *et al.* (1986). Supplementary irrigation (drip) was applied daily to a 0.5 ha block of mixed hybrid seedlings on a coastal estate (marine clay) after a

dry period (no rain for two weeks), except on days after there had been 5 mm or more rain, or it was actually raining. A similar 0.5 ha block acted as the unirrigated control. The trial lasted nearly three years (1981–1983). Annual dry bean yields were increased by irrigation from 1500 to 2400 kg ha⁻¹ (+60%) in 1982 and from 1150 to 1450 kg ha⁻¹ (+28%) in 1983. This followed an increase in pod number (averaging +39%) and in bean weight (+7%). The quantities of water applied were not specified. These results can only be considered indicative of responses to irrigation at this site, and have limited generic value.

In the simulated *El Niño* drought experiment reported by Moser *et al.* (2010) in Indonesia (described above under *Roots and Crop water requirements*) there were no significant differences in cocoa leaf, stem and branch wood, or fine root biomass production (above and below ground) between the control treatment and the one in which rain through-fall was reduced by 70–80%, even though the soil profile dried to permanent wilting point during the year. By contrast, there was a reduction in dry bean production over the year as a whole from 740 ± 180 to 670 ± 30 kg ha⁻¹ (both low yields when compared with the best commercial yields), with the later harvests more affected than the early ones. Possible causes of the limited response to drought in terms of net biomass production were proposed. These included active osmotic adjustment in the roots (measured), high atmospheric humidity in both treatments, and drought mitigation through shading by *Gliricidia*.

In contrast to the trials described above, the principal practical objective of an experiment summarized by Hutcheon (1981b) was to find out if irrigation would induce Amelonado trees to flower throughout the dry season in order to produce pollen for use in manual pollination of a seed orchard in Ghana. When the *cherelles* were continuously removed, irrigated trees produced 30% more flowers than those that were unirrigated, although the flowering patterns were the same. There was no benefit from using over-tree sprinklers (to reduce internal water stress by raising the humidity) rather than micro-sprinklers under the trees.

Drought mitigation

Repeated mulching (with fresh, moist plantain pseudostems) improved the establishment of cocoa seedlings during the extended six-month dry season in Ecuador (Orchard and Saltos, 1988). Mulched plants maintained stomatal opening at similar levels to irrigated plants whilst, at the end of the first year of establishment, there were substantial increases in the dry weight of shoots and roots, and in leaf area over and above those recorded in the irrigated treatments. The benefits of applying a mulch during the first three to four years after establishing cocoa seedlings in the field can be large. But, the cost of growing, cutting, transporting and spreading the mulch can be prohibitive unless it is available on the spot as, for example, when leguminous shrubs such as *Flemingia macrophylla* are used as temporary shade (Wood, 1985c). The role of shade trees in drought mitigation (or enhancement) is complex and variable depending on many variables and is worthy of a separate review.

Specific advice to growers on irrigation practices is even harder to find but the Central Plantation Crops Research Institute, Kerala, South India gives this (edited)

advice to cocoa producers in some areas of southern India, where long periods of dry weather lasting three to six months can occur (CPCRI, 2010):

'Irrigate at weekly intervals during the summer [presumably refers to a sole crop]. When cocoa is grown as a mixed crop with arecanut, irrigate once a week during November–December, once every six days during January–March and once in four to five days during April–May with 175 l water tree⁻¹. Maximum yields are obtained when cocoa is drip irrigated with 20 l day⁻¹ tree⁻¹.'

Assuming a planting density of 1600 trees ha⁻¹ (2.5 m × 2.5 m) these figures equate to rates of water use equivalent to 5.6–7.0 mm d⁻¹ or at 1100 trees ha⁻¹ (3 m × 3 m) 3.9–4.8 mm d⁻¹, and 2.2 or 3.2 mm d⁻¹ for drip irrigation. No estimates of the yield benefits are given or of the total quantity of water to be applied over a season. Presumably this is not known.

Summary: water productivity

1. There is a paucity of reliable published data quantifying the yield and other benefits that could result from well-managed irrigation of cocoa in different locations.
2. It remains to be seen under what conditions irrigation (and/or drought mitigation, including mulching of young trees) is financially worthwhile.
3. Dry air can be expected to limit responses to irrigation.
4. It is not possible to specify yield response functions to water with the limited information available.
5. Shade trees add a further complication.

CONCLUSIONS

Since cocoa is a drought-sensitive crop, and a large proportion of the world's cocoa is grown in parts of the tropics having a distinct alternation between wet and dry seasons, it is to be expected that the water relations of cocoa would have been the subject of research. What is surprising is the limited amount of work done in the field with mature crops as compared with research on immature plants in relatively controlled conditions. Although research on immature plants has led to a good understanding of aspects of cocoa physiology, there is a paucity of information of direct practical value. For example, the lack of data on crop water use and water productivity means it is impossible to quantify yield losses due to drought or yield benefits from irrigation. With the threat of climate change leading to less, or more erratic, rainfall in the tropics, and higher temperatures and drier air, uncertainty in yield forecasting will increase and yields will decrease on average. In particular, there is evidence of a decline in the annual rainfall in the agro-ecological area where cocoa is concentrated in Ghana (Owusu and Waylen, 2009). This may be of particular significance when the existing cocoa is uprooted and the land replanted on soils that have already deteriorated in terms of organic matter and nutrient content. Taken together this could result in crop establishment problems. The vulnerability of the cocoa industry to climate change in Ghana, which employs over 800 000 smallholder farm families on farm sizes ranging from 0.4 to 4.0 ha, has been the subject of a study by Anim-Kwapong and Frimpong

(2006). They proposed a number of policy options that needed to be put in place to enable the industry to adapt to these anticipated changes. These included a drought management policy and, specifically, the promotion of irrigation.

Why has there been this emphasis on fundamental research and less on its practical application? The answer must be in part due to the structure and nature of the industry, and the way research is organised and funded. Often the 'drivers for change' in agriculture are the more progressive farmers who are already industry leaders, but believe they can do it even better given additional information. They will also probably be those with access to funds. Cocoa producers are, however, predominantly (95%) smallholders with very low shadow wages spread over protracted time spans, little if any access to capital and all too often low profitability. Cocoa suffers because the barriers to smallholder entry are very low and people who have few alternative sources of income are prepared to do a lot of work for very little. Most world cocoa production is organic by default – pesticides might be used if insect pests in particular get out of hand – but otherwise there are few purchased inputs, so irrigation has never seemed an option worth pursuing vigorously by researchers (despite the sensitivity of cocoa to water stress).

But perhaps the cocoa industry will develop in a different, more intensive way. Following an eight-year research project, a fledging, modern, mechanised, clonal, cocoa industry is being created in northern Queensland, Australia with supplementary irrigation. Based on field trials, the annual irrigation requirement has been estimated to be up to 470 mm, depending on the site, with peak weekly requirements of about 200 l tree⁻¹ (1250 trees ha⁻¹). Dry bean yields of between 1.5 and 2.7 t ha⁻¹ have been achieved from young trees (Diczbalis *et al.*, 2010).

Research on the water relations and irrigation of cocoa is obviously complicated by such issues as shade/shelter (for relative advantages and disadvantages see Beer (1987) and Obiri *et al.* (2007)), mixed cropping (e.g. with coconut, rubber, banana), diverse scales of production (from smallholders to large estates) and interactions with plant density. All of these variables affect crop water status and the yield potential, and hence the justification (in financial and livelihood terms), or otherwise, for irrigation or other forms of drought mitigation, for example mulching at the establishment phase, appropriate shade usage and planting drought tolerant cultivars (Acheampong, 2010). These are the issues that need to be addressed, preferably in a coordinated international research programme.

Whether managing water stress is justified in a given situation will depend on the growth stage of the cocoa, the local climate and predicted climate change for the region. But when there are still so many other limiting factors to yield, including generally low levels of field maintenance, pests and diseases, lack or imbalance of nutrients and, on occasion, competition from shade trees, water management will not always be the priority issue of concern. Irrigation is a luxury for many farmers. It is 'the icing on the cake' only to be considered when other limiting factors have been addressed. In view of cocoa's international importance as a traded commodity, and whatever the situation, it is difficult to understand why cocoa production at a field level is so under resourced.

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