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REVIEW PAPER

THE WATER RELATIONS AND IRRIGATION REQUIREMENTS OF COFFEE

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SUMMARY

The role of water in the development and yield of the coffee crop (*Coffea arabica* L.) is reviewed. A period of water stress, induced either by dry soil or dry air, is needed to prepare flower buds for blossoming that is then stimulated by rain or irrigation. Although attempts have been made to quantify the intensity and duration of stress required, these have not yet been specified in ways that are commercially useful. Water must be freely available during the period of rapid fruit expansion to ensure large, high-quality seed yields. Depending on the time and uniformity of flowering this can occur at times when rainfall is unreliable, particularly in equatorial areas.

Although there are differences in their responses to drought, commercial cultivars have retained many of the characteristics adapted to the shady environment of the forests in the Ethiopian highlands in which *C. arabica* is believed to have originated. These include partial closure of the stomata when evaporation rates are high as a result of large leaf-to-air saturation deficits (>1.6 kPa), even if the soil is at field capacity. This is thought to be an adaptive mechanism that minimizes transpiration at high irradiances when the leaves are light-saturated.

Our understanding of the actual water use of coffee crops grown in diverse ways is imperfect. For mature crops, well supplied with water, the crop coefficient (Kc) appears to have a value in the range equivalent to 0.7–0.8 times the evaporation from a US Weather Bureau Class A pan. There is some evidence that Kc values are less than this on days when evaporation rates are high (>7 mm d^{-1}). For immature crops allowance has to be made for the proportion of the ground area shaded by the leaf canopy, but this alone may underestimate rates of water use. Present methods of calculating crop water requirements for the purposes of irrigation scheme design and management are imprecise and, probably, subject to large errors depending on local circumstances.

The need for irrigation, and its role in controlling the timing of flowering, varies depending on the rainfall distribution, the severity of the dry season, and soil type and depth. Two geographic areas need to be distinguished in particular; those close to the equator with a bi-modal rainfall pattern and those at higher latitudes with a single rainy season and an extended dry season. Despite the international importance of irrigation in coffee crop production, the benefits to be derived from irrigation, in yield and in financial terms, have not been adequately quantified in either location. Allowable soil-water deficits have been specified for deep-rooting crops (2–3 m) on water retentive soils, usually linked to conventional over-tree sprinkler irrigation systems. Other, potentially more efficient, methods of irrigation are now available for coffee grower use, in particular, micro-jet- and drip-irrigation systems. However, there appears to be little advice, based on sound experimental work, on how to design and operate these to best advantage.

There is a need to interpret and apply the scientific understanding of the role that water plays in the growth and development of the coffee plant into practical advice that can assist the grower to plan and to use water efficiently, whether rainfall or irrigation, for the production of reliable, high-quality crops. Future research opportunities are identified.

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INTRODUCTION

The centre of origin of *Coffea arabica* L. is considered to be the cool, shady environment in the understorey of forests in the Ethiopian highlands. At these latitudes (6–9°N) and altitudes (1600–2000 m asl) the mean average air temperature is in the range 15–20°C, the annual rainfall is 1600–2000 mm and there is a single dry season lasting three to four months. Only relatively recently has coffee been grown in open sunny situations, including regions closer to the equator where there are two annual dry seasons (Cannell, 1985). Many of the fascinating physiological characters of coffee can best be understood by recalling the conditions under which *C. arabica* evolved, particularly its response to water.

By comparison, *C. canephora* (Pierre ex Froehner) occurs wild in the lowland equatorial forest extending from West Africa to Lake Victoria. Still known popularly as *Robusta* coffee it grows best in areas where the mean annual temperature is around 26°C (Wrigley, 1988). *C. canephora* represents about 20% of the world trade in coffee and is an important crop in Indonesia, Ivory Coast, Cameroon and Uganda. *C. liberica* (Bull ex Hiern), another lowland species, contributes less than one per cent of the total. Unless otherwise stated, this review concentrates on *C. arabica*.

Commercial plantations are distributed from Hawaii (20–25°N) and Cuba (22°N) to Parana State, Brazil (22–26°S). The coffee plant is an evergreen, and leaves are produced throughout the year at rates that are dependent on temperature and water availability, but are shed during periods of drought. Temperatures below 12°C for long periods inhibit growth and development and, above 24°C, net photosynthesis begins to decrease and is negligible at 34°C (Nunes *et al*., 1968). Prolonged exposure to high temperatures (*c*. 30°C) accelerates leaf loss and induces a general decline in tree health (Drinnan and Menzel, 1995). In equatorial areas (Kenya, northern Tanzania and Colombia), *C. arabica* is usually grown at altitudes above 1000 m. That the crop is very susceptible to frost damage limits the areas (latitude and altitude) suitable for commercial production. Maestri and Barros (1977) have previously reviewed ecological aspects of the physiology of the coffee crop.

The useful product is the bean, relatively heavy seeds that ripen within sweet red fruits. The seeds, rich in caffeine, form the basis of a beverage widely traded and consumed throughout the world. In Ethiopia, flower and fruit development are phased to maximize the likelihood that the fruit will expand during the rains and after a flush of new leaves. Hence floral initiation occurs during the cool, dry winter period; the flowers then remain dormant during the dry season, and blossom after the first showers that invariably precede the main rains. The 'pinhead' fruits remain dormant before expanding after the beginning of the rains by which time the new flush of leaves, triggered by the same 'blossom' showers, have expanded. Intense rainfall throughout the year (without dry seasons) can lead to scattered harvests and low yields (Cannell, 1985).

This phenological cycle, is followed very closely in most non-equatorial coffee growing areas (such as southern India, Hawaii, Central America, south-central Brazil, Malawi and Zimbabwe, as well as Ethiopia), but in Kenya and Colombia, countries close to the equator, fruit expansion can often coincide with drought. It is against this background of two contrasting ecological areas, where commercial *C. arabica* is predominantly grown, that the development, water relations, water requirements and irrigation of the coffee crop are considered here.

CROP DEVELOPMENT

Vegetative growth

Coffee shoots have two distinctive structural features: (i) the axil of each opposite and decussate leaf contains not one, but a series of buds: and (ii) branching is dimorphic. The orthotropic (vertical) shoots produce plagiotropic (horizontal) branches from the topmost 'head of series' bud, whilst the lower buds remain dormant or produce more orthotropic shoots (or, occasionally, inflorescences). The inflorescences develop from the buds at each node on the plagiotropic branches. These usually produce flowers only once, so pruning has to be done to ensure a continued supply of flowering nodes (Cannell, 1985).

Water stress reduces rates of shoot extension, the number of nodes and the area of individual leaves (Boyer, 1969 for *C. canephora*; Fisher and Browning, 1979; Tesha and Kumar, 1979). Also, Wormer (1965) observed that shoot growth rates can be restricted before there is any evidence of differential stomatal closure between irrigated and unirrigated trees. In Kenya, new leaves emerge most rapidly during synchronous growth flushes that occur after rainfall, but usually only when this is accompanied by a rapid temperature drop (defined as 3°C in 40 minutes). Flushes are most marked during the hot dry season (January to March) and occur at this time after rainfall even on irrigated trees (Browning, 1975a), indicating the action of some stimulus associated with rainfall, but independent of soil water status. Trees irrigated after eight weeks of enforced drought flushed immediately, producing leaves faster than trees that had been irrigated regularly (Browning and Fisher, 1975). Trees irrigated after twelve weeks of drought, did not respond in the same way: rather, they produced 70% more lateral shoots than did trees that experienced shorter periods of drought. Tesha and Kumar (1979) have also observed these examples of compensatory vegetative growth following the relief of water stress (particularly at high levels of nitrogen fertilizer) in Kenya, as have Drinnan and Menzel (1994) in Australia. Browning and Fisher (1975) postulated that the reason might be due to a reduction in root resistance to water uptake following a stress-induced build up of abscisic acid.

Flower buds

There are four successive stages of coffee flower bud development. After initiation they grow for several months, reaching an average length of 4–6 mm before becoming dormant, a state associated with high levels of endogenous abscisic acid. Flower bud dormancy is slowly broken by continuous water stress over a period of 1–4 months. This stress can be induced by dry soil and/or large evaporative demand associated with high temperatures and large saturation deficits of the air (Browning, 1975b). After several weeks of water stress the flower buds, as with shoots, can be stimulated to grow again by the relief of water stress following rain (or irrigation) or by a sudden drop in temperature and/or increase in atmospheric humidity, changes associated with the onset of rain. During the three to four days after the stimulus has been received, meiosis occurs and there is a large increase in the giberellic acid content that is thought to overcome the inhibiting effect of abscisic acid (Browning, 1975b). During the next 6–12 days the water content of the flower buds increases rapidly and they grow in length three- to four-fold, developing to blossoming and anthesis at a rate that is temperature dependent. A period of water stress, therefore, appears to be mandatory for normal flower bud development (Alvim, 1960; 1973).

At Campinas in Brazil (lat. 22°50′S), Magalhaes and Angelocci (1976) attempted to quantify the level of water stress needed to allow flowering to occur by making simultaneous measurements of the water potential of dormant flower buds and the subtending pair of leaves, under varying levels of water stress (cv. Mundo Novo). They found that buds had to experience critical water potentials below -1.2 MPa for flowering to be stimulated by irrigation. This threshold value was associated with a change in the direction of water movement from a net flow into the buds, from the subtending leaves, to a net flow out of the buds. When irrigation was applied, there was a rapid influx of water into the buds and flowering occurred within 7–10 days, but only if buds had experienced water potentials below -1.2 MPa. In ecological terms, this synchronous blossoming mechanism may protect the sexual structures of the flower buds from water stress during dry periods, in the same way that winter dormancy in temperate areas protects plant tissues from frost damage (Browning, 1975b). Also in Brazil, Astegiano *et al.* (1988) subsequently confirmed that a period of water stress was an essential pre-requisite for flowering to occur. Using detached branches and tracers, they were unable to show that the subtending leaf, or the water potential gradient between this leaf and the flower bud, affected this process. Instead they suggested that the signal for the break in dormancy was full turgidity of the buds.

Crisosto *et al.* (1992) reported the results of a similar study in Hawaii (lat. 21°21′N; alt. <100 m asl). Here the aim was to identify ways of improving the uniformity of flowering to facilitate mechanical harvesting. From a series of detailed field and glasshouse experiments they found that flower opening was stimulated by irrigation after a single period of water stress if pre-dawn leaf water potentials declined below -0.8 MPa. Similar stimulation of flowering was observed when less severe but more prolonged water deficits were imposed ($\psi L = -0.3$ to -0.5 MPa for two weeks). In both cases, flowering only occurred in buds that were at the 'open white cluster' stage of development when water stress was imposed. At this time, secondary xylem tissue is in the process of being formed. In split-root experiments, where one half of the root system was droughted and the other well irrigated, flowering was stimulated in the same way as in plants in which both parts of the root system were kept dry. This indicated that it was a 'root signal', perhaps a cytokinin or a giberellin, from the dry part of the root system that stimulated flowering independently of the leaf water potential. From these observations they concluded that, in leeward areas of Hawaii, frequent irrigation to prevent flowering followed by a controlled water deficit and then re-irrigation may represent a practical way of synchronizing flowering and shortening the period of harvest. In a greenhouse study, Schuch *et al.* (1992) found, however, that gibberellic acid only partially compensated for insufficient water stress for flower initiation. Trees that experienced leaf water potentials below −2.65 MPa, and flower bud water potentials of about −4.0 MPa, flowered within about nine days after irrigation. These stress levels are much greater than those Magalhaes and Angelocci (1976) found to be necessary to stimulate flowering in Brazil.

Again with the aim of trying to synchronize flowering to allow non-selective mechanical harvesting, Drinnan and Menzel (1994) conducted experiments with potted plants (cv. Catuai Rojop and Mundo Novo), in a heated greenhouse in Queensland, Australia (lat. 27°S). They found that water stress did not affect the timing of flowering that only occurred when the photoperiod was less than 12 hours. Severe water stress (leaf water potential allowed to fall to −2.5 MPa before re-watering) reduced the number of inflorescences, indicating that irrigation was needed during floral initiation. Water stress accelerated flower development but had no deleterious effects on flower differentiation. They concluded that stressing of trees in the late stages of flower development, after initiation is complete, provides a means of increasing the proportion of fully differentiated dormant flower buds (stage 4) on a tree. The effects of temperature on the initiation and development of flowers of several cultivars, grown in pots under glass, independent of water status, have also been investigated by the same authors (Drinnan and Menzel, 1995). Floral initiation did not occur at temperatures above 28°C, nor when the photoperiod was longer than 13 h. There was little difference between cultivars in these responses.

Fruit growth

For the first six to eight weeks after fertilization, the ovaries undergo cell division but the fruits grow very little, remaining as so called 'pinheads'. From about 6–16 weeks after blossoming, the fruits increase rapidly in volume and weight mostly owing to pericarp growth. The two fruit locules swell to full size and the endocarps that line the locules lignify. Thus, it is during this swelling stage that the maximum volume of the seeds (beans) is determined (Wormer, 1966). The size to which the locules grow depends greatly on the water status of the trees at this time; fruits that expand in wet weather will have larger beans than those that develop during hot, dry conditions (Cannell, 1974). From 12–18 weeks after blossoming, the beans are formed and begin to fill the locules, increasing rapidly in dry weight with little increase in fruit size. About 30–35 weeks after blossoming, the fruits ripen, losing chlorophyll, producing ethylene and turning red. During this time the pericarp increases in dry weight and volume. The growing fruits act as priority sinks for assimilates and minerals, and can draw carbohydrates from elsewhere in the tree. This may lead to dieback of branches when yields are excessive (see below).

In Kenya, the proportion of large, commercially valuable coffee beans (those retained on a 6.75 mm sieve) varies greatly within and between years. Cannell (1974) analysed the results of three long-term field trials at Ruiru (lat. 1°4′ S; alt. 1610 m asl). He found that about 50% of the between-year variation in large beans could be explained by the number of rainy days (>1 mm rainfall) 10–17 weeks after flowering, the period when fruits were expanding most rapidly. Irrigation and mulching are the two most important field treatments that have a beneficial effect on bean size. In equatorial areas such as Kenya, floral initiation can occur almost throughout the year (Wormer and Gituanja, 1970) and periods of fruit expansion will not always coincide with one of the two short annual wet seasons. By contrast, in areas away from the equator with a single, annual and reliable rainy season, fruits are more likely to develop during periods of adequate rainfall (Clowes and Wilson, 1974; Clowes and Allison, 1982).

Components of yield

The seed yield (Y; kg ha^{-1}) of coffee can be represented by the following equation:

$$Y = p.N.F.Wf.S$$

where: p = tree density (ha^{-1}); N = fruiting nodes (tree^{-1}); F = fruits (node^{-1}); Wf = fruit weight (kg fruit^{-1}); S = seed:fruit weight ratio

Most of the world's coffee has been planted with fewer than 2000 trees ha^{-1} with one, two or three stems per tree. These are usually pruned to 2 m height or less. However the greatest yields per unit area are obtained with densities of 4000–10 000 trees ha^{-1} (Cannell, 1985). At the higher densities, there is a reduction in the number of fruits per tree (thought to be due to the effect of mutual shading on floral initiation), but the mean weight per seed remains fairly constant. The yield of individual trees at conventional spacing is highly dependent upon the number of potential flowering nodes produced the previous year. This number varies considerably from year to year and is the component affected most by treatments such as irrigation, mulching and fertilization.

The number of fruits per node also varies from season to season, with fruit set in the range 20–80%. Poor fruit set can be caused by (a) atrophy, attributed to prolonged drought or excessive rainfall during initial stages of flower bud development, and/or (b) inadequate pollination or fertilization owing to heavy rain, low temperatures or a shortage of pollinators at blossom time.

According to Cannell (1985), under favourable conditions 12–20 fruit can be set per node, each of which carries two 3000–4000 mm^2 leaves. Even when the leaves at non-fruiting nodes are included, coffee is able to set more fruit than it can sustain. Some fruit shedding does occur, principally during the period of rapid fruit swelling. This shedding is exacerbated by drought, as well as by other factors. Even after drought, numerous fruits may remain and the trees are said to 'overbear'. In extreme cases the vegetative shoots die back and very few potential flowering nodes are produced for the next season. This problem is especially serious in young trees that often need to be de-blossomed.

Drought can, therefore, reduce (a) the number of fruiting nodes per tree, (b) the number of fruits per node, and/or (c) the size of the seed depending, on its timing and severity. The effect on final yield, however, will depend on whether the number of fruits that remain is greater or less than the number that can be sustained by the tree, which is a function of leaf area. Over-bearing, by contrast, will lead to a reduction in the potential number of flowering nodes, with implications for yields in the following year.

Drought symptoms

A summary of field observations written by Clowes and Logan (1985) for growers in Zimbabwe (lat. 17–20°S; alt. <1500 m asl) is given below.

- Drought reduces the rate of production of new leaves; leaves are smaller and internodes are reduced in length, especially on fruit-bearing branches.
- Old leaves turn yellow and are shed prematurely, particularly on sides of trees exposed to the afternoon sun.
- Extension growth ceases prematurely, particularly on fruit-bearing branches, thereby restricting or delaying flower bud initiation; this adversely affects the following year's crop.
- There may be insufficient leaf area to support the current crop. This not only reduces yield and quality but can also lead to dieback of shoots, again with implications for the next crop.
- During the early expansion phase (10–12 weeks after flowering) drought will cause fruits to become blue/green before being shed; severe stress a little later causes fruits to yellow, and the seeds to blacken and wither.
- Stress at the end of this phase (up to 17 weeks after flowering) will reduce the final size of bean as the parchment skin is laid down. Severe wilting will cause fruit to feel spongy and beans may become desiccated.
- Stress when the seeds are developing results in ragged beans with a reduced mass.
- Stress also delays ripening and the fruits take longer to turn red. Severe water stress, leading to dieback of the branches, causes the fruit to blacken.

Root depth and distribution

Early studies on the root growth of coffee were made by Nutman (1933a; b; 1934) and by Bull (1963) in northern Tanzania and Kenya (lat. 1–3°S; alt.1250–1700 m asl), areas of bimodal rainfall (up to *c.* 1500 mm annual total). Nutman (1933b) described a 'normal' root system developed by transplanted seedlings as comprising one or more main vertical (or tap) roots, a superficial layer of lateral roots in surface layers of soil growing horizontal to the surface, and other deeper laterals arising from the tap roots but growing downwards at an acute angle to the vertical.

The depth and distribution of roots varies with many soil physical and chemical properties, as well as with cultural practices such as mulching, irrigation, nitrogen fertilization and tree spacing. For example, Bull (1963) undertook a detailed study of the long-term (20 years) effect of mulch (banana trash) and irrigation on the root growth of two clones. The root systems of 20 trees were excavated (two per irrigation × mulch treatment combination for each clone), and the roots separated into the components, weighed and counted. Irrigation reduced the penetration depth of the tap root (by 0.56 m or *c*.20%) and the development of primary (defined as roots with axes >5 mm in diameter) and secondary roots (any root subtended by a primary root) in deeper layers of the soil (a deep volcanic clay loam) profile. In the surface layers irrigation increased the *length* of lateral roots and the number of lateral secondary roots. Mulching, by contrast, increased both the size of lateral and 'sinker' roots (derived from lateral primary and secondary roots), and the depth of tap root penetration. There was a dense mass of fibrous roots in the surface layers beneath the mulch. The combination of mulch and irrigation gave the 'best-developed' root system, but the maximum root depth was still reduced by about 0.5 m. However, in all the treatment combinations, roots extended to depths below 2 m.

Wallis (1963), summarizing earlier work in Kenya, stated that roots of unirrigated coffee could explore the top 3 m of soil (a deep, red laterite clay loam), although the bulk (80%) of the roots were in the top 1.2 m. In studies of the water use of coffee, Pereira (1957), Wallis (1963) and Blore (1966) found that, in dry years, the soil at depths of 3 m would reach permanent wilting point as defined by the sunflower test.

In Veracruz, Mexico (19°10′N: alt. 1225 m asl), Garriz (1979) excavated roots of 24-year-old plants to depths of 1.8 m (cv. Typica and Pluma Hidalgo) and 2.4 m (cv. Bourbon) in a loamy clay soil. With all three cultivars, about 50% of roots (dry mass), with diameters of 2 mm or less, were found in the top 0.6 m.

At Chipinge in Zimbabwe (20°13′S: alt. 1130 m asl), Cassidy and Kumar (1984) found that, in the absence of any physical or chemical impediment, roots could extend to depths of 2.5 m (on deep, well-drained slightly acid loamy soils). On heavier soils with high silt contents, root development was severely restricted and axial roots rarely extended much below 1.0 m. Soil compaction, gravel strata and high water tables all restricted root growth. They too found that mulch enhanced root growth in the top 0.25 m, although mulching had less effect at high plant populations (>4000 ha^{-1}) due to mutual shading and self-mulching. They also reported that axial roots of six- to seven-year-old irrigated trees (cv. SL 28) penetrated deeper (by about 0.5 m) at high plant densities (4–6000 ha^{-1}) than at low densities. This has implications in terms of the responses of both traditional and higher-density planted coffee to drought and to irrigation (Fisher and

Browning, 1979). The lateral spread of surface roots was constrained by the influence of neighbouring trees, whether planted at high densities or as a cova (more than one tree at each station). Axial roots of trees planted in a cova also grow deeper (to 3.5 m) than those of single trees at similar densities. Clowes and Logan (1985) summarized these results, and concomitant practical implications, for growers in southern Africa.

In a recent investigation at Ngapani in Malawi (14°S: alt. 1200 m asl), axial roots of young (unmulched, seven months from field planting), immature (third year after planting) and mature (more than four years after planting) drip-irrigated coffee, extended to depths of 0.45, 1.2 and >1.5 m respectively (cv. Catimor 129, spaced at 3.6 × 1.2 m). The majority of feeder roots were found in the top 0.5 m (young) and 1.25 m (immature) depth of the deep clay loam soil within 0.3 and 0.8 m from the main stem respectively (Sanders, 1997). Inter-row soil compaction restricted root proliferation in the topsoil. At Ngapani the annual effective rainfall is about 800 mm. There was no evidence at this location that drip irrigation during the extended dry season caused the roots to be concentrated in the wetted soil volume. Where soil depth restricted rooting (to 0.9 m) there was evidence (pre-dawn $\psi L < -2.0$ MPa after 24 days without rain or irrigation) that these plants became water-stressed earlier than did plants ($\psi L = -0.6$ MPa) growing where there were no depth restrictions (>1.2 m).

Root extension

Huxley and Turk (1975) reported preliminary studies at Ruiru, in Kenya, on factors affecting the extension growth of the fine white roots. From observations made against glass windows in an underground root laboratory, they found that roots grew throughout the two-year study, with fine roots remaining alive for at least this period. ‘Clumps’ of roots were active in producing fine roots at different times. Rapid rates of root extension generally preceded shoot extension. There was little effect of crop or irrigation on the growth of these roots. The authors acknowledged that these observations were made on a limited number of trees, and that there was a great deal of variability that could not be adequately explained. Cannell (1972) also found from a growth analysis study that the feeder roots (<3 mm diameter) continued to grow almost unchecked during periods of rapid shoot growth at the start of the main rains. Roots also grew rapidly during the cool dry weather, when shoot growth was slow. In general, roots grew more continuously than shoots. In another study at Ruiru in Kenya, and using a radioisotope of phosphorus placed at different depths (down to 1.8 m) and distances from the main stem (to the mid-row at 1.35 m), Huxley *et al.* (1974) found that the relative activity of roots changed markedly with season, except at depths of 1.8 m. After prolonged drought, relatively high root activity was found at mid-depth near to the trunk but, after the soil was re-wetted by rain, most root activity occurred in the topsoil at quarter row distance. After the soil profile had been wet for some time, functional roots were more evenly distributed than this. The position of maximum root activity frequently did not coincide with the distribution of fine roots of this mature crop. The authors commented on the variability of the data obtained using this technique.

Cuenca *et al.* (1983) stressed the importance of the superficial root system that extended into the litter layer, including root hairs attached to the surfaces of decomposing leaves, in the absorption of mineralized nutrients. From a study in Miranda State in Venezuela (lat. 10°N; alt. 1400 m asl) on mature unfertilized coffee grown in an acid soil under heavy shade, they found that about one third of the total dry mass of fine roots (less than 1 mm in diameter) to a depth of 0.5 m were located in the top 0.1 m of soil. Root production in the litter layer, however, was very variable and transient. According to Wrigley (1988) there is little evidence that mycorrhizae are present on coffee roots.

PLANT WATER RELATIONS

Physiological aspects of the water relations of coffee have been studied for more than 60 years beginning, perhaps, with the classical work of Nutman (1937a; b; 1941) in northern Tanganyika (now Tanzania). There were similar studies in Brazil, Costa Rica and Mexico by Alvim (1960), Butler (1977), Fanjul *et al.* (1985) and, in Kenya, by Wormer (1965), Browning and Fisher (1975), Fisher and Browning (1979) and Kumar and Tieszen (1980a; b). Other names associated with this work include Nunes (1976) and Bierhuizen *et al.* (1969). More recently, the results of fundamental research in Hawaii by Meinzer and co-workers have been reported (Meinzer *et al.* 1990; Crisosto *et al.* 1992; Gutierrez *et al.* 1994), and in Brazil by Barros *et al.* (1997). Over the period covered, many new field techniques for measuring plant water status have been introduced, including the diffusion porometer, the pressure chamber (Angelocci and Magalhaes, 1977), the infra-red gas analyser, and the sap flow method for estimating transpiration. Much ingenuity has been shown by individual scientists, particularly by Nutman in his pioneering studies during the 1930s in East Africa. In this section, an attempt is made to reconcile the results of some of this work, carried out under contrasting conditions and with different facilities and techniques.

Stomatal behaviour

Stomata are only found on the abaxial surface of *C. arabica* leaves at densities variously quoted in the range 150 to 330 mm^{-2} (Franco, 1939; Wormer, 1965; Josis *et al.*, 1983; Wrigley, 1988; Da Matta *et al.*, 1997). Stomata are also present in green fruits at densities of 30–60 mm^{-2} that may represent 20–30% of the photosynthetic surface on heavily bearing trees (Cannell, 1985).

Nutman (1937b) used a homemade recording resistance porometer to make measurements of diurnal changes in stomatal opening under shaded and sunny conditions in northern Tanzania (lat. 3°30′S; alt. 1370 m asl). He found that stomata opened early in the morning, but remained fully open throughout the day only when it was overcast, or when leaves were shaded from direct sunlight. If the incident radiation levels were high, there was a rapid reduction in stomatal conductance (even when all the other leaves on the tree were removed). On days when wilting of the youngest leaves was observed, stomata in the other leaves had closed by midday and stomatal conductance remained low for the rest of the day, even when leaves were shaded. The stomata were observed to respond to changing ambient conditions within three minutes. Subsequently, partial closure of the stomata was also observed on sunny days in Brazil and in Costa Rica (references cited by Maestri and Barros, 1977), and in a glasshouse experiment in the Netherlands (Bierhuizen *et al.,* 1969).

In Kenya, Wormer (1965) and later Browning and Fisher (1975) used the infiltration technique (liquid mixtures of isopropanol and distilled water) to measure the effects of soil water availability on stomatal opening. They too observed partial closure of the stomata during the day, even in irrigated trees. Wormer (1965) showed how increasing air temperatures (over the range 22 to 33°C), saturation deficits (0.2 to 2.4 kPa) and daily total solar radiation levels were each associated with a linear reduction in the degree of stomatal opening during the afternoon. For example:

$$\mathrm{IS} = 18.5 - 0.365\ \mathrm{T}$$

where: IS represents the infiltration score (scale 1–14), a large number indicating that the stomata are wide open, and T the air temperature in the field (°C). This equation was found to be valid for observations made between 11.30 and 16.00 hours (local mean time) and explained 93% of the variation in the measured infiltration score.

In pot experiments, Wormer showed that relative stomatal opening was closely related to the soil water content. However, in a field experiment, the relationship was only satisfactory during extended periods of dry weather that were not interrupted by rain. Like Nutman (1937b), he too found that the degree of stomatal opening was always greater in shaded leaves than in ones exposed to the sun. Interestingly, Wormer also observed that the application of nitrogen fertilizer (100 kg N ha^{-1}) increased stomatal opening, particularly in irrigated trees.

Wormer found that the degree of stomatal opening in unirrigated trees did not return to the level observed in irrigated trees for several months after the rains began. By comparison, Bierhuizen *et al.* (1969), in a pot experiment, noted a lag of only four to five days after watering before there was full recovery. By contrast, Browning and Fisher (1975) reported that the degree of stomatal opening (as recorded at 14.00–15.00 hours) increased, for up to four weeks after the relief of stress, to values 1.4 to 1.6 times greater than those recorded in trees previously irrigated at weekly intervals. This last effect was most marked when drought had been imposed for about eight weeks, by which time the potential soil-water deficit (0.5 $\mathrm{E_{pan}}$) had reached about 300 mm.

In Bahia, Brazil (lat. 15°S), Butler (1977) measured stomatal conductances on sunlit leaves of *C. canephora (*cv. Guarini) as low as 0.4 – 0.5 mm s^{-1} in the middle of the day, compared with 1.0–1.5 mm s^{-1} on shaded leaves at the same time. On cloudy days, values were typically 2.0 mm s^{-1}. Butler also found that temperatures of (horizontal) leaves were often 10–15°C warmer than the prevailing air temperature (29°C), but 1–2°C cooler when shaded. The temperature differential (δT,) was related to the net radiation absorbed by the leaf (Rn, W m^{-2}) as follows:

$$\delta T = 0.0264\ Rn - 1.07\ (r = 0.92)$$

Low stomatal conductances (0.4–0.5 mm s^{-1}) were associated with positive leaf-air temperature differences exceeding 10°C, with corresponding large saturation deficits of 4.5 to 6.0 kPa. When leaf and air temperatures were similar, the calculated stomatal conductance was about 1.8 mm s^{-1}, close to those measured on shaded leaves. These values were derived from an energy balance analysis, with assumed aerodynamic resistances of 35 s m^{-1} for individual leaves. In contrast to results reported for *C. arabica,* Butler found that after 'substantial' rain the stomata of sunlit leaves did not close, in spite of temperatures exceeding 30°C.

Insufficient information was given by Butler (1977) to assess the role of soil water availability, or of atmospheric humidity on the stomatal conductances. Fanjul *et al.* (1985) were, however, able to demonstrate the sensitivity of stomatal responses of young seedlings (cv. Typica) to changes in the saturation deficit of air at constant temperatures (day 25°C/night 15°C). At low (shade) irradiance (200 μmol m^{-2} s^{-1}, photosynthetically-active radiation (PAR) equivalent to about 44 W m^{-2}) raising the saturation deficit from 0.2 to 1.5 kPa reduced stomatal conductances (measured with a continuous flow porometer) from about 3.0 to 0.7 mm s^{-1}.

Fanjul *et al.* (1985) reported similar measurements made in field experiments at two sites in Veracruz State, Mexico (lat. 19°27–31′N, alt. 1225–1340 m asl). These confirmed that stomatal conductances were larger in shade-grown plants (cv. Bourbon and Caturra) than in sun-grown ones (1100–1200 trees ha^{-1}). At dawn, values in sun-grown plants were large (12 mm s^{-1}), but they normally decreased during the day (to about 4 mm s^{-1}) as total irradiance (0–800 W m^{-2}), air temperatures (14–26°C) and saturation deficits (0–1.6 kPa) increased. At higher values of each of these variables though (e.g. 1000 W m^{-2}, 26–30°C, and 1.6 – 2.8 kPa respectively) the stomata remained closed all day. By contrast, under shade, stomatal conductances continued to increase during the morning (reaching 20 mm s^{-1}) before declining during the afternoon.

More recently, Barros *et al.* (1997) reported the results of measurements (cv. Red Catuai) in southeast Brazil (lat. 20°45′ S; alt. 650 m asl). They found that stomatal conductances (measured with a diffusion porometer) during the main growing season, were relatively high in the early morning but declined throughout the day, as air temperatures and saturation deficits increased from 20 to 30°C, and from low values to 2.0–3.0 kPa respectively. In contrast, during the winter months, conductances were low throughout the day, observations that they attributed to low night temperatures.

In a detailed study in Hawaii (lat. 21°54′ N; alt. 98 m asl), Gutierrez *et al.* (1994) using a gas exchange system, also found that stomatal conductances (cv.

Yellow Catuai) were typically high in the morning and declined after midday as the saturation deficit (leaf-to-air) and PAR levels increased. After normalizing for changes in PAR, the observed diurnal hysteresis in the relationship between conductance and the saturation deficit was removed, revealing a strong negative relationship with the dryness of the air. This was especially the case when canopy conductances, expressed on a unit leaf area basis, were plotted. They also showed that an increase in wind speed could reduce canopy conductance as a result of the transfer of dry air to the leaf surface. From these and other observations they concluded that stomatal control of water fluxes from the canopy of a well-watered coffee crop was strongly influenced by the interaction of wind and atmospheric humidity. Differences in the proportion of net radiation dissipated through transpiration from irrigated crops between two years at the same location were also attributed to the sensitivity of the stomata to the leaf to air saturation deficit (Gutierrez and Meinzer, 1994a).

In a comparative study of gas exchange in different species in Colombia (lat. 3°31′ N; alt. 1020 m asl), Hernandez *et al.* (1989) showed clearly how stomatal conductances in shaded plants (cv. Arabigo) declined rapidly, reaching about 90% of the initial value when the leaf-to-air vapour pressure difference reached 4.0 kPa. This was judged to be due to the inherent sensitivity of the stomata to dry air rather than to concurrent changes in the bulk leaf water potential, or to changes in intercellular carbon dioxide concentrations. In a controlled environment study in Japan, Kanechi *et al.* (1995) have also shown how stomatal conductances decline in well-watered plants as the saturation deficit of the air increases over the range 1.0 to 3.0 kPa with almost complete closure of the stomata at the dry end of this range under natural daylight. There was a corresponding rise in leaf temperatures from about 25 to 35°C.

Photosynthesis

Nutman (1937a) also pioneered the measurements of photosynthesis in coffee. At Lyamungu, in northern Tanzania, he observed that apparent rates of assimilation of carbon dioxide were relatively constant during days when it was cloudy, but fell to low values during the middle of the day when the sun was shining. Rates of assimilation were maintained if leaves were shaded, naturally or artificially. He attributed the midday suppression of photosynthesis in sunlit leaves to the effects of large incident levels of solar radiation on stomatal opening. Later Bierhuizen *et al.* (1969) reported the results of a pot experiment carried out under controlled conditions (25°C day/20°C night; 70% relative humidity) in a glasshouse in the Netherlands. As the soil dried from field capacity to permanent wilting point, there was a reduction in the rate of photosynthesis. Unusually, there was a time lag before there was a corresponding reduction in transpiration (see below).

At Ruiru in Kenya, Kumar and Tieszen (1980a) studied the effects of light intensity and temperature on rates of photosynthesis of container-grown seedlings (cv. SL28). Leaf and air temperatures were controlled by varying the temperature of the circulating water in the leaf chamber, but there was no corresponding control of the saturation deficit of the circulating air. The saturating photon flux density (PFD) for shade-grown plants was about 300 μmol m^{-2} s^{-1}, half the value for sun-grown plants, and much less than the peak values of 2500 μmol m^{-2} s^{-1} recorded in the tropics. These PFD values approximate to about 66 and 550 W m^{-2} respectively. Rates of photosynthesis declined at temperatures above 25°C but, surprisingly in view of the results reported above, stomatal conductances remained constant over the temperature range 25–35 °C. This was thought to be due to an increase in mesophyll resistance to carbon dioxide diffusion. In a similar field study, Kumar and Tieszen (1980b) found that rates of photosynthesis (at temperatures of 24 ± 2°C and irradiance of 300 μmol m^{-2} s^{-1}) closely matched ($r = 0.96$) concurrent changes in stomatal conductance (g, diffusion porometer) over a range (-0.6 to -3.5 MPa) of leaf water potentials (ψL). Rates changed from 1.6 g m^{-2} h^{-1} (when $\psi L = -0.6$ to -1.0 MPa and $g = 1.25$ mm s^{-1}), through 1.2 g m^{-2} h^{-1} ($\psi L = -1.0$ to -2.0 MPa; $g = 1.0$ mm s^{-1}) to 0.4 g m^{-2} h^{-1} ($\psi L = -2.8$ to -3.5 MPa; $g = 0.3$ mm s^{-1}).

In Mexico, Fanjul *et al.* (1985) found that rates of photosynthesis of young seedlings (cv. Typica) grown in a controlled environment declined rapidly once stomatal conductances fell below about 2.0 mm s^{-1} at a low (200 μmol m^{-2} s^{-1}) irradiance (PAR) level. Changes in rates of photosynthesis tended to match changes in stomatal conductance (over the range 0.5 to 3.0 mm s^{-1}). Both conductance and photosynthesis declined as the saturation deficit of the air increased from 0.2 to 1.5 kPa. By contrast, at Palmira in Colombia (lat. 3°31′N; alt. 1020 m asl), Hernandez *et al.* (1989) showed how the rate of uptake of carbon dioxide in shaded plants remained relatively unchanged as the leaf-to-air vapour pressure deficit increased from 0.5 to 1.5 kPa but then decreased almost linearly as the vapour pressure deficit rose further to 3.5 to 4.0 kPa.

In Hawaii, water stress reduced the total leaf area of container-grown plants, but assimilation rates on a unit leaf area basis were always similar. Meinzer *et al.* (1992) suggested that this represented an important process by which coffee adjusts to reduced water availability. Measurements of carbon isotope discrimination (intrinsic) and gas exchange (instantaneous) failed to give consistent estimates of water use efficiency. In Brazil, Da Matta *et al.* (1997) found that *C. canephora* (cv. Kouillou) was superior in photosynthetic performance to *C. arabica* (cv. Red Catuai) in stressed and unstressed plants. They attributed this, in part, to differences in stomatal density.

According to Cannell (1985), there are four notable features concerning the photosynthetic rate of leaves of *C. arabica,* all of which seem to reflect its evolutionary history as a shade-adapted C3 species:

- The maximum net photosynthetic rates of *sun* leaves are low (around 7 μmol CO_2 m^{-2} s^{-1} at 20 °C) but higher (up to 14 μmol CO_2 m^{-2} s^{-1}) for *shade* leaves that contain more chlorophyll per unit area than do sun leaves.
- The saturating irradiances for photosynthesis are low (500–600 μmol m^{-2} s^{-1}

of PAR for sun leaves, and about half this for shade leaves). This compares with irradiance (PAR) levels of 2500 μmol m^{-2} s^{-1} at midday on sunny days in the tropics. These values approximate to about 110–130 and 550 W m^{-2} PAR respectively.

- The net photosynthetic rates decrease markedly with increases in leaf temperatures above 20–25°C. This may be due to increased mesophyll resistance (Kumar and Tieszen, 1980a) but in the field, high temperatures are often associated with low leaf water potentials, which cause midday stomatal closure and an increase in internal CO_2 concentrations. On sunny days in the tropics, leaves can reach temperatures of 35–40°C, as much as 10–15°C above ambient (Cannell, 1971; Butler 1977).
- Even with light-adapted sun leaves, the photosynthetic apparatus seems to be physically damaged by continuous exposure to high temperatures.

At the other end of the temperature range, Bauer *et al.* (1985) showed, in a detailed controlled environment study in Austria, how chilling of above ground tissues at night ($\leqslant$6°C for 12 h) impaired the photosynthetic process recorded the next day (at 24°C). Depending on the chilling temperature, it took from two to six days for photosynthesis to return to the value for the control treatment. Chilling on successive nights at 4–6°C reduced photosynthesis progressively on each day following treatment. Conditioning the plants failed to reduce these effects. About 25% of the chilling effect was shown to be due to reduced stomatal conductance and 75% to impairment of the carboxylation process. These observations confirm the circumstantial evidence that chilling injury contributes to determining the limits to successful coffee production due to altitude and/or latitude. In a follow-up study, Bauer *et al.* (1990) found that cultivars differed in their response to chilling stress. Using a derived index of susceptibility, relatively resistant standard cultivars were identified (K7, SL28 and K33), confirming field observations made in Zimbabwe during a cold spell.

The primary production rate of mature trees benefits from mutual shading, with up to 90% of the total radiation intercepted by the top ‘layers’ of leaves. Nevertheless, the radiation and heat load is sufficiently spread to enable four- to five-year-old trees in Kenya to attain net assimilation rates similar to those of seedlings (Cannell, 1971). The potential annual primary production of closed canopies of unshaded coffee seems to be 20–30 t ha^{-1}, equivalent to those of tea, oil palm and many tropical forest plantations. Compared with other trees, coffee of all ages allocates a relatively large proportion (up to 40–45%) of net annual dry matter increment to leaves (Cannell, 1972). Leaf area indices of between 7–11 have been recorded for closely spaced trees with access paths.

Transpiration

In northern Tanzania, Nutman (1941) measured the transpiration rates of whole trees over five-minute intervals using an ingenious, sensitive continuous-weighing device. He found that at low total radiation levels (630 W m^{-2})

transpiration increased with radiation, but at higher levels (840 W m^{-2}) the relationship was less clear due to stomatal closure. Daily totals of transpiration correlated well with cumulative radiation and the mean saturation deficit of the air during daylight hours. Reducing radiation levels by 70% with a hessian cloth only cut transpiration by individual trees by about 10% compared with unshaded plants. Using the stem heat balance technique in Hawaii, Gutierrez and Meinzer (1994b) recorded transpiration rates similar to those previously determined by Nutman (1941) more than 50 years earlier.

In Colombia, Hernandez *et al.* (1989) showed how transpiration rates from individual (shaded) leaves rose as the leaf-to-air saturation deficit increased to 1.0–1.5 kPa, but then declined rapidly as the dryness of the air increased to 4.0 kPa. By comparison, transpiration from sunflower leaves continued to increase, but at a declining rate, over the same range. In Japan, Kanechi *et al.* (1995) found that transpiration from one-year-old plants (cv. Typica) in a greenhouse, measured with a steady state diffusion porometer, was always greater on cloudy days compared with sunny days for both well-watered (especially) and droughted plants. These differences, which reached a factor of three, were attributed to the sensitivity of the stomata to the leaf-to-air saturation deficit, and not simply to radiation levels. Stomatal conductances declined logarithmically with increasing leaf temperatures and saturation deficits. When the values of these two variables exceeded about 30°C and 2.0 kPa respectively, the stomata were virtually closed, even in well-watered plants.

Because of the capacity of stomata to control water loss, relative turgidity measurements do not appear to be a good measure of plant water status. Bierhuizen *et al.* (1969) recorded daytime values between 92%, when the soil was close to field capacity, and 80% at permanent wilting point. Nunes and Correia (1983) found, in a controlled environment study, that the Catuai group of cultivars could support smaller relative leaf water contents (76–81%) without wilting than could the Caturra group (85–90%).

In Kenya, however, Fisher and Browning (1979), Kumar and Tieszen (1980b) and Gathaara and Kiara (1984) have successfully used a pressure chamber to measure leaf water potentials (ψL) during the day in the field. Kumar and Tieszen (1980b) found that when mid-afternoon temperatures were 25–30°C, and saturation deficits had reached 2.5–3.0 kPa, ψL fell to minima of about -1.5 Mpa (even when the soil was close to field capacity) before increasing again in the late afternoon. When the soil profile was relatively dry (soil water content below 50% of field capacity in the top 1.2 m) the corresponding minimum value of ψL was -2.8 MPa, but recovery in the late afternoon was rapid. On cloudy or overcast days (saturation deficits 1.1–1.2 kPa) minimum values were only -1.0 to -1.2 MPa. By comparison, Fanjul *et al.* (1985) recorded minimum values of ψL in Mexico of about -0.8 MPa during the middle of sunny days in sun-grown plants and, sometimes, down to -1.4 Mpa even under natural shade. Both ψL and stomatal conductances were sensitive to changes in the saturation deficit of the air. However, on occasions when the stomata closed during the day,

ψL could remain relatively high (-0.6 to -0.8 MPa) suggesting that stomatal closure limited the reduction in ψL and prevented excessive transpiration.

Drought resistance

Cultivars are known to differ in their responses to drought. For example, experience in Zimbabwe, reported by Clowes and Logan (1985), suggests that the dwarf cultivar Caturra (a mutant, first identified in Brazil) is relatively drought-tolerant, despite a large amount of foliage. However, because it fruits late in the dry season it can suffer from drought at that time. Similarly K7, selected in Kenya and with a spreading habit of growth, appears to be able to withstand hot dry conditions in Zimbabwe. By comparison, cultivars SL28 and SL34 (both also selected in Kenya) are thought to be more susceptible to drought than either Caturra or K7, but less so than Geisha or Agaro, which are both of Ethiopian origin. Elsewhere Wrigley (1988) stated that Laurina and San Ramon (both mutants) were considered to be relatively drought-resistant.

Only a limited amount of work appears to have been done to identify the reasons for these differences between cultivars. Nunes (1976), in a review of the water relations of coffee, referred to some of her earlier work in which the responses to drought were compared in pot experiments. Those in the Caturra group appeared to have a faster rate of water use than others, and to be able to dry the soil to lower soil water potentials. Yet others differed in their capacity to retain leaves after the first sign of wilting, with Agaro and KP 423 (from Tanzania) responding well. Previously, in Uganda, Dancer (1963) had also identified apparent differences between seedlings in their responses to drought (measured in terms of vegetative growth).

In neighbouring Burundi (lat. 3°12′S; alt. 1570 m asl), Josis *et al.* (1983) compared 11 cultivars in terms of the relative changes in leaf water potentials between the beginning and the end of the dry season. The trees had been planted in the field four years earlier at a density of 2500 ha^{-1}. They identified four which maintained higher water potentials than the others when droughted, namely, Catuai Vermelho (compact growth habit, from Brazil), Mbirizi Temoin (Rwanda), Mysore (India) and ABK 5718 (Ethiopia). They recommended that these cultivars should be planted in marginal areas. For measuring leaf water potential they used a hydraulic press, which previous work had shown gave results very close ($r = 0.97$, $n = 58$) to those obtained with a pressure chamber (Renard and Ndayishimie, 1982).

From a comparative study with container grown plants in Brazil, Da Matta *et al.* (1993) concluded that coffee is a ‘water saving’ rather than a ‘dehydration tolerant’ species. They recorded similar but limited (-0.34 MPa, 22%) osmotic adjustment in five cultivars subjected to water stress, but slightly more (-0.48 MPa) in the single *C. canephora* cultivar tested. Proline was an important component of this process (Maestri *et al.*, 1995). Effective stomatal control maintained high relative leaf water contents.

Previously Meinzer *et al.* (1990), in Hawaii, had observed osmotic adjustment in field-grown plants when subjected to drought. This, together with increases in tissue elasticity, had reduced the leaf water potential at which turgor loss occurred. There was considerable variation between cultivars in the rate at which leaf water deficits developed, with Mokka showing the biggest decline in leaf water potential as the soil dried. In a controlled environment study, Renard and Karamaga (1984) compared the responses to drought of two cultivars. Caturra Amarelo, from Brazil, was able to maintain its leaf water status, as measured by a number of techniques including osmotic potential, better than Harrar, from Ethiopia. Similarly, Venkataramanan and Ramaiah (1987) showed how, in South India, cultivars differed in their responses to drought largely as a result of differences in the capacity of the young plants to adjust the osmotic potential through, mainly, the accumulation of proline. In general, cultivars of *C. arabica*, particularly San Ramon, could endure drought better than could those of *C. canephora*.

Other attempts have been made to develop procedures for identifying potentially drought-tolerant cultivars. Thus, Meguro and Magalhaes (1983) in Brazil compared the responses of five cultivars to water stress in terms of the activity of the enzyme nitrate reductase, leaf diffusion resistance, and leaf xylem water potential (using a pressure chamber). The results, obtained with one-year-old seedlings that were transferred to a controlled environment immediately before the start of the experiment, showed a linear reduction in nitrate reductase activity as leaf water potentials declined. One cultivar (Catuai) was identified as possibly being more tolerant of drought than another (Naçional). There were no significant differences though between cultivars in the sensitivity of stomatal activity to changes in leaf water potential; stomatal conductances always decreased linearly ($1.0–0.16\ \mathrm{mm\ s^{-1}}$) as leaf water potentials fell (-1.0 to -3.0 MPa) with correlation coefficients (r) ranging from 0.69 ($n = 23$) to 0.91 ($n = 26$).

Clearly, differences exist between cultivars of both *C. arabica* and *C. canephora* in their responses to dry soil (and air) conditions (Montagnon and Leroy, 1993). The mechanisms responsible, though, are less clear. As Jones *et al.* (1985) have pointed out, heterogeneous tree crops are much closer to their wild relatives than are most short-term agricultural crops, because of the long-term nature of breeding programmes. Nevertheless there are differences between cultivars in their responses to dry soil (and air), although the mechanisms responsible are less clear. For a grower it is the capacity of trees to survive and achieve a reasonable yield under adverse conditions that is important.

CROP WATER REQUIREMENTS

Evapotranspiration

Much of the early work on investigating and quantifying the water use of field-grown coffee was carried out close to the equator in Kenya (lat. 1°4′S; alt. 1610 m asl), at the Coffee Research Station, Ruiru (Pereira, 1957; 1967; Wallis

1961; 1963; Blore, 1966). Comparisons were made between measured changes in the soil water content in the 3-m deep profile with evaporation from a tank of water (1.2 m diameter) either raised above the ground or sunken. Pereira (1957) initially used an empirical factor (f) to convert E_{pan} (sunken) to an estimate of coffee water use (ET_{crop}). Its value ranged from 0.8 during the middle of the rains down to 0.5 during the dry season when the leaf area was least. For irrigated crops in the dry season, 'f' was assumed to decline by 0.1 (from 0.8) for each 10-day period without irrigation, (or reverting to 0.8 when rainfall $> E_{pan}$) until it reached the value corresponding to that for unirrigated coffee for that month. It was assumed that, within the 3-m deep profile, all the water was available to the crop, and that the transpiration rate declined at the rate of 0.25 mm d^{-1} until the deficit reached 325 mm, when it ceased. If the soil was at field capacity (defined as the water content at 33 kPa suction), excess rain was assumed to drain immediately below the root zone.

Using this model, Wallis (1963) reported the results of 15 comparisons of actual changes in soil water content made over the period 1950 to 1962. The general level of agreement between computed and measured soil water deficits (SWD) was good for unirrigated crops ($r^2 = 87\%$, range SWD 30–270 mm), but less good for irrigated crops ($r^2 = 65\%$, range SWD 0–115 mm). There was a tendency to overpredict deficits during periods of severe drought. This was thought by Wallis to be due to the false assumption that roots could extract easily all the available water within the 3-m deep profile.

Wallis (1963) showed that measurements of evaporation from a sunken 'Kenyan' pan gave estimates of E_o closer to those obtained using the 1948 version of the Penman equation than a raised pan (with a grid), particularly during periods of high evaporative demand. Blore (1966) developed this work with two further years of measurements of changes in soil water content, at a distance of about one metre from each tree, and derived the following relationship:

$$ET_{crop} = (0.86\text{–}0.0033D)\ E_{pan}$$
$$(r^2 = 36\%; P < 0.01)$$

where ET_{crop} is the total water use over a ten day period (mm), D is the mean soil water deficit at the end of this period (mm) and E_{pan} is the corresponding mean total evaporation (mm) from a sunken Kenyan pan.

When soil water was not limiting i.e. at deficits taken to be less than 100 mm (Wormer 1965), the relationship was simplified to:

$$ET_{crop} = 0.86\ E_{pan}$$

The former equation, when extrapolated, predicts that transpiration will cease when D reaches 270–295mm. This work was done on clean-weeded coffee (except for a flush of weeds at the start of the rains) spaced at 2.7 × 2.7 m. Blore considered that his model predicted actual water use by an unirrigated crop more precisely than did Pereira's method. Because of the smaller range of deficits and the difficulty of quantifying drainage, however, the estimates for an irrigated crop lacked the same precision. In this location, the rate of water use from irrigated crops ranged from about 2 mm d^{-1} in July and August to 3.8 mm d^{-1} in January to March. Annual water-use totals averaged about 850 mm use for an unirrigated crop and 940 mm for an irrigated crop (825–1050 mm). This compared with E_{pan} (sunken) values of about 1500 mm, and annual rainfall totals of 1040 mm (Wallis, 1963).

Further from the equator, in Zimbabwe, the recommended method for calculating the water requirements of an irrigated crop has been to use an ET_{crop}: E_{pan} ratio for mature trees (>3 years old) in the range of 0.55 to 0.75. The exact value depended on the method of irrigation used, and whether or not the crop was mulched. E_{pan} in this case refers to evaporation from a standard United States Weather Bureau (USWB) Class A pan (Wilson and Pilditch, 1978). For younger trees, the Et_{crop}: E_{pan} ratio for a mulched crop was taken to be equal to the proportion of the soil shaded by the tree canopy, and could be as low as 0.2 in the first year after planting.

In Zimbabwe and Malawi (lat.11–20°S), growers using drip irrigation were advised to include a ‘canopy factor’ to allow for the age/size/planting arrangement of trees when estimating irrigation water requirements. Defined as the ‘ratio of the canopy area to the planted area’ it can range in value, for example, from 0.03 for one-year-old, to 0.62 for five-year-old trees spaced 3.05 × 2.4 m apart (1366 stations ha^{-1}) with two trees per station (Clowes and Logan, 1985). Thus:

$$ET_{crop} = (0.6\ E_{pan}) \times \text{‘the canopy factor’}$$

Subsequently, Logan and Biscoe (1987) have suggested that, in Zimbabwe, the pan coefficient, when used with an USWB Class A evaporation pan, should be 0.8 and 0.7 for mature unmulched and mulched coffee respectively, rather than 0.6. This method was widely used for calculating the irrigation water requirements in southern Africa, although it fails to allow for the effects of, for example, climatic factors on stomatal opening. Hess *et al.* (1998) have recently pointed out that this approach seriously underestimates the water use of young coffee, since it only takes into account the canopy cover and ignores the effects of crop height, leaf area and other microclimatic factors that can influence the water use of widely spaced tree crops.

The most detailed measurements of the water balance of a coffee crop have been made in Hawaii (lat. 21°54′N; alt. 98 m asl). In this island climate, Gutierrez and Meinzer (1994a) used the Bowen ratio and stem heat balance methods for estimating the actual water use of a commercial crop (cv. Yellow Catuai) at different stages (age-related) of canopy development (leaf area index, $L = 1.4$–7.5). When the crop, grown in hedgerows, was well-irrigated (drip) latent heat loss was the most important component of the energy balance at all stages of development (*c.* 60% of the net radiation at $L = 6.7$). Evaporation from the soil surface and from inter-row vegetation ranged from 40% of total evapotranspiration at $L = 1.4$ down to nearly zero at $L = 6.7$, when the crop almost completely shaded the soil surface. Interestingly, the proportion of net radiation dissipated as latent heat was less in the year when the leaf-to-air saturation deficit was high (1.68 kPa) than when it was lower (1.35 kPa). This was judged to be the result of associated variations in stomatal conductances. Evaporation from the crop ($L = 6.7$) began to decline within four days of irrigation ceasing but returned to normal two days after it was resumed. This followed 25 days without irrigation. Wilting was observed when the proportion of the net radiation dissipated as latent heat fell from 60 to about 30% of the total.

Crop coefficients (Kc) were calculated using data derived from this study:

$$Kc = ET_{crop} / ET_o$$

where ET_{crop} is transpiration by the coffee trees plus evaporation from the inter-row, and ET_o is potential evapotranspiration calculated for a reference crop, grass or alfalfa, using the Doorenbos and Pruitt (1977) version of the Penman equation.

The weather data were collected from an automatic station. Kc averaged 0.55 ($L = 1.4$) in the second year after planting at spacings of 3.6 × 0.7 m, and reached 0.68–0.82 ($L = 5.4$–6.7) for plants more than two years in the field. In the first year ET_o rates were in the range 4.4–6.6 mm d^{-1}. Interestingly, in the following year, for plants of a similar age ($L = 3.4$–4.2), Kc values were about 30% less (0.45). It was suggested that this was due to the higher ET_o rates (7.4 mm d^{-1}) experienced in that year compared with the one before (Gutierrez and Meinzer, 1994b). When irrigation ceased Kc values declined within four to five days, halving in value, from 0.8 to 0.4 after 18 days ($L = 6.7$). At this stage the leaves were visibly wilting ($\psi L = -2.14$ MPa), but transpiration was continuing at about 30% of its original value, suggesting that substantial gas exchange was still taking place.

In the most recent FAO manual on crop evapotranspiration (Allen *et al*., 1998), the tabulated Kc values presented for coffee are in the range 0.9–0.95 for a clean-weeded crop, and 1.05–1.10 for a crop with weeds, when using the FAO version of the Penman-Monteith equation to estimate ET_o. These values are for well-managed crops, 2–3 m tall, grown in a sub-humid climate (minimum relative humidity *c*. 45%). If, instead of a single coefficient, Kc is derived from its two constituent components, transpiration and bare soil evaporation, the corresponding values are given as 0.80–0.90 and 0.85–0.90 respectively, assuming a dry soil surface. The validity of these values remains to be seen.

In a review of the ecology of the coffee crop, Barros *et al*. (1995) cited values for the albedo (0.15–0.19) for several cultivars, and the roughness lengths (Z_o) for Caturra at two spacings (2.0 × 2.0 m, tree height (Z) = 2.9 m, $Z_o = 0.42Z$; and 2.0 × 1.0 m, $Z = 1.7$ m, $Z_o = 0.20Z$). The corresponding zero planes of displacement (d) were 0.42Z and 0.55Z. They concluded that our knowledge of the actual water use of coffee crops grown in diverse ways, with contrasting energy balances and aerodynamic profiles, and depending on such factors as location, cultivar, spacing, pruning system and, in some places, on the type and density of shade, was very limited.

Drought mitigation, planting density and shade trees

Before irrigation is considered, every attempt should be made to minimize the adverse effects of drought through less expensive and appropriate water conservation practices. Clowes and Logan (1985) have made the following recommendations to growers in Zimbabwe.

- Planting two or more trees at each station (known as the *cova* system) is considered to be more appropriate in drought conditions than the hedgerow system, partly because roots extend deeper in the soil.
- Ratooning is also seen as a way of reducing the effects of drought. This should be done on a five to eight year cycle; trees in the middle of this period, with large crops borne mainly on primary branches are considered to be susceptible to drought and to respond to irrigation more than trees at the beginning (new vegetative growth) or end (more higher-order branches) of the growth cycle.
- Mulching reduces evaporation from the soil surface and improves infiltration of water into the soil. However, the effects on yield seem to be additional to those of irrigation, probably through its influence on nutrient availability, aeration and perhaps soil temperature. Mulching is particularly important in young coffee. The importance of mulching has long been recognized in Kenya (Pereira and Jones, 1954; Njoroge and Mwakha, 1985) and Tanzania (Robinson and Mitchell, 1964).
- Weed control, effective and timely, is clearly also important as a water conservation technique.

These are some of the measures open to growers who are either unable to irrigate or who have insufficient water to cover the whole area adequately. Many of them though are associated with good cultural practices, whether for irrigated or unirrigated coffee.

In Kenya, Fisher and Browning (1979) found that planting at high densities, over the range 5000 to 20 000 ha^{-1}, did not increase the susceptibility of individual plants to drought, and may even have alleviated it, at least up to the highest practical density (8000 ha^{-1}). They based these conclusions on measurements of leaf water potential, stomatal opening (infiltration score), rates of extension of lateral branches and the number of nodes. Similarly, Gathaara and Kiara (1984) found no evidence, based on measurements of leaf water potentials, that increasing tree density from 1322 to 6610 ha^{-1} (cv. SL28) increased plant water stress in dry weather. These, perhaps unexpected, responses were explained on the basis that mutual shelter must have reduced the evaporative demand within the crop canopy and, as a result, water use per unit of land area did not increase with density. Factors, other than concern about drought susceptibility, therefore, will determine the optimum planting density for any location.

C. arabica is a shade-adapted species, but the effects of shade trees on the physiology, water use and yield of this crop, and others, are complex (Willey, 1975). In terms of crop water relations, the presence of shade trees can: (a) reduce the incident solar radiation; (b) reduce maximum air temperatures (e.g. by

5.5°C); (c) increase minimum air temperatures (by 1.5°C); (d) reduce the saturation deficit of the air (by 0.2 kPa); (e) change the aerodynamic roughness of the cropped area; (f) reduce evaporation (by 40% from a Piche evaporimeter), and (g) modify the interception and throughfall of rainfall. The values cited are those measured by Barradas and Fanjul (1986) in a study comparing the microclimate in a heavily shaded (*Inga jinicuil*) crop with a similar unshaded area in central Veracruz State, Mexico (lat. 19°31′N; alt. 1225 m asl). The net effect on crop water use and water-use efficiency (taking into account water use by the shade trees themselves) will depend a great deal on the local situation and as yet there is no predictive model to enable this relationship to be quantified in a useful way. Shade trees do, of course, influence the ecological conditions, soil and microclimate in which crops grow in many diverse ways (Huxley, 1999). For example, in Kenya, shading is used to reduce weed growth in coffee where the costs of weeding are high, and to elevate night temperatures at high elevations in order to reduce chilling damage.

In support of this practice, Baggio *et al.* (1997) and Caramori *et al.* (1996) have recently shown in Brazil how shade trees (*Grevillea robusta* and *Mimosa scabrella* Benth. respectively) can reduce damage caused by radiation frosts, a major and unpredictable cause of yield loss when minimum air temperatures fall to −3 to −4°C. In these areas (20–24°S) frost protection with sprinkler irrigation at night, as practised in some temperate fruit orchards, is not considered to be economic. Cultivars differ to a limited extent in their susceptibility to frost damage (Filho *et al.*, 1986).

IRRIGATION

Yield responses

In view of the importance of irrigation in commercial coffee production, it is perhaps surprising that few experiments have been reported that quantify, with precision, the yield, quality and financial benefits, that can be derived, and the parameters by which irrigation systems should be designed and managed. Assessing the irrigation need of coffee is not straightforward; in particular there are two principal ecological areas to consider: (a) equatorial, with two short (sometimes unreliable) rainy seasons; and (b) sites distant from the equator with seasonal climates and single rainy seasons. There are also the maritime climates of Hawaii. In addition, altitude effects air temperature and potential evaporation rates.

Bi-modal rainfall areas. Wallis (1963) reported the results of experiments carried out at Ruiru, close to the equator in Kenya between 1957 and 1961. Excluding the 1958 data, a total of 1900 mm irrigation water was applied in the four-year period. This led to a total yield increase of 370 kg ha^{-1} (or 12%) of clean beans, an average response of 0.77 kg ha^{-1} per mm of water applied. The biggest effect though was on the yield of large, grade ‘A’ beans which increased by over 60%

(see also Cannell 1974). These experiments were conducted on conventionally spaced trees (1300 ha^{-1}). Yields from the unirrigated crop averaged 1.98 t ha^{-1}.

Previously, attempts had been made in northern Tanzania (lat. 3° 30′S; alt.1370 m asl) to quantify the responses to irrigation in an experiment that began in 1940 and continued until 1955. Pereira (1963) highlighted the difficulties in interpreting the data when, for much of the period, there was no satisfactory way of estimating crop water requirements using sound scientific principles. For the first ten years of the experiment there were cumulative yield benefits from irrigation, despite its arbitrary nature. For the next eight years there were no consistent benefits, as a result, it is claimed, of unsound irrigation practices. Mulching (banana trash) though was always beneficial (Robinson and Mitchell, 1964). Irrigation experiments are difficult to manage with any crop, but particularly with coffee because there is uncertainty about actual rates of water use and the role that water plays in controlling the time and duration of flowering.

In a later experiment in Kenya, the application of 400 mm water increased red fruit (cherry) yield of cv. SL 28 by 1.4 kg $tree^{-1}$ in one year (Cannell, 1973). For a planting density of 2250 trees ha^{-1}, this is equivalent to 3150 kg ha^{-1}. Assuming a weight ratio of fresh fruit to sun dried (*c.* 11% water content) clean green beans of 6:1, (a value that appears to remain relatively constant regardless of treatment), this represents a (bean) yield increase of 1.3 kg ha^{-1} for each mm of water applied, i.e. nearly double the figures derived from the data reported by Wallis (1963). This corresponding base yield of clean beans was about 3.7 t ha^{-1}. These results apply to crops irrigated with over-tree sprinklers that wet the whole land area.

More recently, Gathaara and Kiara (1988) reported the results of a three-year (1984–1987) irrigation rate × frequency experiment, also at Ruiru in Kenya. Although the results were incomplete, irrigation during both dry seasons appeared to increase annual yields of clean beans (cv. French Mission, planted at a density of 1333 trees ha^{-1}), but by only about 9% (or 167 kg ha^{-1} a^{-1}) over the three years. There was a larger effect on the proportion of grade 'A' beans, which increased from 30 to 43% of the total seed weight. There were no significant effects of irrigation depth (38, 76 and 100 mm) or frequency (at intervals of 14, 21 and 28 days) on bean yields that averaged about 2.1 t ha^{-1}.

Planting densities now range from 2600 to 5000 ha^{-1}, thereby influencing the responses to drought and hence to irrigation through effects on the size and shape of the crop canopy, and the depth and distribution of roots. Thus, Kiara and Stolzy (1986) reported that in the first year after tree establishment, at Ruiru in Kenya, drip irrigation increased yields (cv. SL 28) from about 1200 to 1500 kg ha^{-1} at a low tree density (1322 ha^{-1}, but with two stems per tree). At a high density (5288 ha^{-1}) the absolute yield increase was larger than this (4100–5100 kg ha^{-1}), but there were no further yield benefits at the next highest density (6610 ha^{-1}). In the following year there was a smaller effect of density on clean bean yield, from 3100 to 3900 kg ha^{-1} for the irrigated crop, and 2200 to 2700 kg ha^{-1} for the rain-fed crop. Unfortunately insufficient information was given in the paper to allow the results to be interpreted with more precision than this. A previous paper, however, had reported how irrigation and tree density had influenced certain components of yield (Gathaara and Kiara, 1985). Irrigation (and high densities) increased vegetative growth but reduced the number of nodes and the number of fruits per node and per primary branch, especially in the lower parts of the canopy. This was thought to be the result of a reduction in the transmission of light within the canopy. The yield benefits resulting from irrigation in Kenya must therefore be associated with the production of large fruits and seeds (Cannell, 1974). Fisher and Browning (1979) had previously suggested that irrigation in Kenya should be withheld for a period during each dry season, in order to reduce vegetative growth and to enhance flowering so that the yield benefits could be maximized, but reducing stem extension could limit the potential crop in the following year. This idea does not yet appear to have been evaluated in experiments.

Based on the results of the early experiments by Wallis (1963), growers in Kenya were advised to irrigate crops, rooting to depths of about 3 m in deep clay loam soils at normal spacing, when the soil water deficit reached 150 mm, and then to apply 100 mm (net) of water. A deficit of 150 mm represents a depletion of about 50% of the available water in the root zone. Assuming no rain, this means that the irrigation interval was about 40 days from June to August, 25 days from September to October and 20 days from December to March. These were the recommendations for overhead sprinkler systems. Total net annual irrigation water requirements ranged from 140 to 800 mm (mean 400 mm) depending on the season. Later, following the results of the experiments described by Gathaara and Kiara (1988), it was concluded that 38 mm applied every 21 days was a realistic practical schedule to follow. This compared with the earlier recommendations for growers to apply 76 mm at monthly intervals. Akunda and Kumar (1981) have suggested that decisions on when to irrigate could be based on the time taken for a dry cobalt chloride paper disc to change in colour from blue to pink, when attached to the abaxial surface of a leaf. If this exceeded 4–5 minutes during the middle of sunny days in Kenya, corresponding to leaf water potentials of about -2.0 MPa, then irrigation should be applied. This technique was evaluated in South India using seedlings and field-grown plants of *C. canephora* with the conclusion that the critical leaf water potential was similar, about -1.9 MPa, which corresponded to 7.5 minutes for the colour change to occur.

Unimodal rainfall areas. Africa south of the equator ($>8°$S), experiences a single rainy season from November–December to March–April followed by a long dry season which is initially cool but, depending on the altitude, can become hot. The importance of these differences is illustrated by the following analysis by Wilson and Pilditch (1978). At Chipinge, in the Eastern Highlands of Zimbabwe (20°13′S) irrigation is deliberately withheld for up to two months towards the end of the dry season (peak $E_{pan} = 6–7$ mm d^{-1}) to break flower bud dormancy.

Flowering is then stimulated by the onset of the rains. The exact duration of the dry period depends on the depth and type of soil. By contrast at Karoi, in northwest Mashonaland (16°48′S) peak evaporation rates can reach 9–10 mm d^{-1} in the same two months (September and October), and these hot dry conditions before the onset of the rains, alone provide sufficient internal water stress to break flower bud dormancy. The increase in atmospheric humidity, or cooling, at the start of the rains then provides the stimulus to induce flowering. Figure 1 attempts to highlight these differences between locations close to and away from the equator in relation to stages of yield development and irrigation need.

On water-retentive soils (AWC > 140 mm m^{-1}) deeper than one metre, the recommendation is to apply a net 50 mm water at Chipinge, or 65 mm at Karoi, at the equivalent soil water deficits. Net average annual irrigation water requirements range from 380 mm at Chipinge to 740 mm at Karoi, for crops irrigated with over-tree sprinklers, with peak net monthly requirements of 75 mm and 135 mm respectively, and minimum irrigation intervals of 12–14 days (Wilson and Pilditch, 1978). On shallow or sandy soils, the recommendation is to apply 45 mm net at 10-day intervals. It is not clear on what experimental evidence these

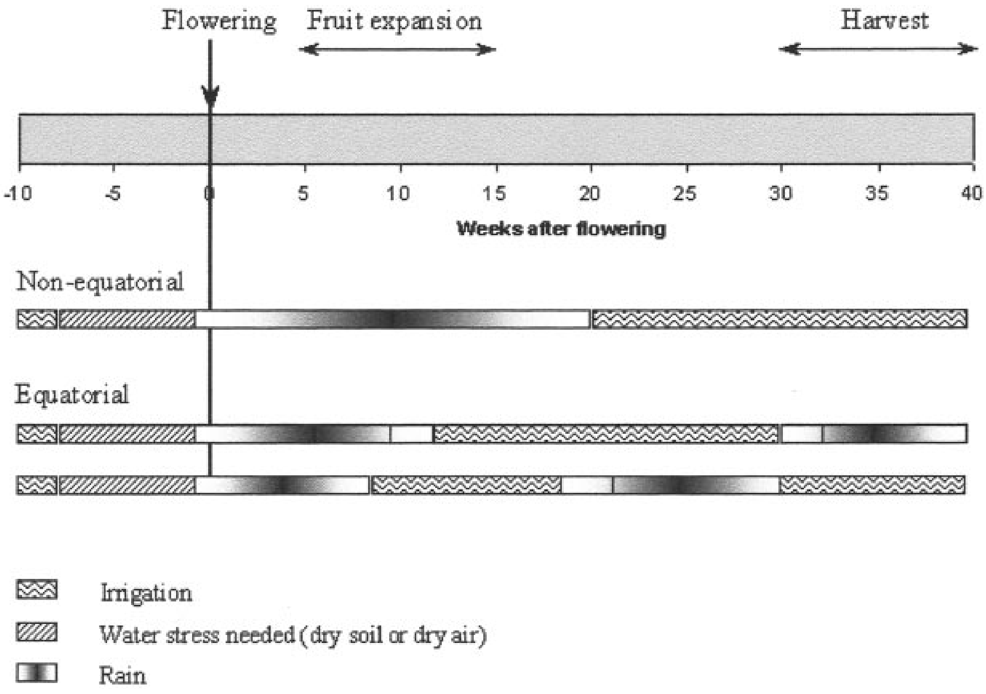

Figure 1. Stages of yield development in coffee in Africa after flowering has been stimulated by the start of the rains, following a period of water stress in (a) non-equatorial areas and (b) equatorial areas at the start of: the 'long' rains (upper line); and the 'short' rains (lower line). The extended dry seasons, when irrigation may be beneficial, are indicated; it may be necessary, also, to supplement rainfall with irrigation during periods of fruit expansion.

recommendations are based. There appears to be no published data describing the yield benefits to be derived from irrigation for these locations.

In the Australian states of Queensland (17°S; alt. 15–700 m asl) and northern New South Wales (28°S; alt. sea level), where coffee is largely machine harvested, the recommendations are to irrigate trees regularly, at three- to seven-day intervals, during the periods of floral initiation and development (stages one to four), ensuring that there are no large fluctuations in plant water status during stage four as the flower buds approach maturity (Drinnan, 1995). Water stress is then applied by withholding irrigation until the first signs of wilting and the leaf water potential declines to -2.5 MPa (pressure bomb). This level of stress is then maintained for three to four weeks by daily (morning) applications of small quantities of water (1–2 l/tree, drip irrigation) in order to prevent tree damage and leaf fall. After eight to ten weeks of water stress the soil profile is then brought back to field capacity as quickly as possible, to encourage rapid uniform flowering. If rain interrupts this sequence early in the cycle – during the first three weeks – the advice is to continue to impose stress even though some flowering will occur. Should rain fall in mid-cycle – four to six weeks after stress was initiated – the recommendation is to wet the top 0.15–0.20 m of soil if the flower buds are observed to begin to enlarge within two to three days of the rain. This will allow these flower buds to develop normally. Water stress is then re-imposed to trigger flowering of the remaining buds at the specified time. Rain late in the cycle – seven to ten weeks after stress was initiated – induces the need to bring soil back to field capacity immediately. The aim in this region is to synchronize flowering so that it occurs over the shortest possible period in order to ensure that a large proportion of the total crop can be machine harvested, preferably in a single pass. This may require a series of drought cycles if rain falls during the period of stress. Supplementary irrigation is also applied, as needed, during the period of rapid fruit expansion.

Methods

There is a large choice of irrigation systems suitable for coffee. Because irrigation is largely supplementary, and the topography of coffee areas is uneven, conventional surface or flood irrigation is not commonly practised. Within two broad systems there is a wide choice of irrigation methods, similar to other orchard crops:

- over-tree sprinkler systems which can be fully portable, semi-portable or fixed (a so-called solid set system); and
- under-tree systems including mini-sprinkler, micro-jet, drip and basin irrigation.

All these methods are currently used in coffee and each has its relative advantages and disadvantages in terms of capital cost, labour requirements, operating costs, water application efficiency, ease of operation and maintenance, and flexibility to adjust for trees increasing in size. The choice of method will vary depending on the requirements and constraints (e.g. capital, labour, topography, water availability and quality, mechanization, and technical support by manufacturers and suppliers) of individual producers. In this section the main criteria influencing the choice of system and its design, with particular reference to coffee, are considered.

Over-tree systems. These are based on conventional medium-pressure sprinklers (0.3–0.4 MPa) on tall risers spaced at, say, 9 × 12 m. The main and lateral lines can either be portable or fixed. Using such a system, the whole land area will be irrigated, including the access paths and inter-row areas. It has been estimated in Colombia that about 5 mm of water is needed to saturate a coffee tree (3.5 years old, single stem, spaced 1 × 2 m) and to wet the lower surface of the leaves (Guzman and Gomaz, 1987). This depth of water is needed, therefore, before water reaches the soil surface, each time the crop is irrigated. The crop is likely to remain wet for 4–17 hours after irrigation ceases depending on the time of day when irrigation begins (05.00–17.00 h respectively). The operating efficiency of sprinkler systems of this type can be as high as 80–85%, depending on operating conditions including wind speed and direction but, with a widely spaced row-crop like coffee, it is difficult to be precise. Over-tree systems allow chemicals to be washed off leaves, and associated cooling can induce flowering. Centre-pivot and linear-move irrigators have also been used successfully in coffee, for example, in Zambia and Queensland respectively.

Under-tree systems. It is often more sensible to apply water directly to the soil below the tree, and to minimize the amount of water applied to the inter-rows that only encourages weed growth. Small under-tree sprinklers mounted on skids can be attached to a long flexible small-diameter PVC pipe. The pipe is pulled to a new position (usually at intervals of 6 m) from the end of a row at fixed times, and usually operates in alternate pathways at a 6 × 6 m spacing. Although low in labour requirements, this system still applies water to the inter-row areas, and application rates can be high.

Micro-jets are an alternative system in which small, low pressure sprinklers or micro-jets are attached directly to a small diameter PVC pipe running down each row. Depending on tree spacing these jets, mounted on their own plastic stand, are spaced at intervals of about 2–2.5 m. The wetted diameter is about 3–4 m, and application rates are about 14 mm h^{-1}. One sprinkler may serve more than one tree. With tree crops it is not necessarily important to wet all the rooting volume of soil, providing roots have access to sufficient water within part of the root zone. This will require careful checking in the field. Each row is irrigated in sequence. The lateral pipes can be moved from one row to another if necessary, but there is increased risk of damage to the irrigation system and perhaps to the trees.

Drip irrigation has become popular for coffee in recent years. This method allows precise quantities of water to be applied at frequent, but as yet unspecified, intervals. Providing the system is well designed, with good filtration, it is ideal for coffee and has the advantage that, if necessary, nutrients can be mixed with the water. The system can also be adjusted, by increasing the size or number of the emitters, to apply more water as the trees get bigger. However, the critical issue with drip (or trickle) irrigation is the need to specify what proportion of the root zone needs to be wetted, and to ensure that the water spreads laterally in the soil. On sandy soils, there is a risk that the water will move vertically below the depth of roots with limited lateral spread: in such cases, microjets are likely to be more appropriate. The lateral line with emitters can be placed either on the soil surface or, if there is a risk of damage during weeding for example, or to make it easier to see that all the emitters are working, fixed about a metre above the ground for easy viewing and maintenance. Emitters are usually spaced between 0.7–1.0 m apart along the line, and apply water at rates of 2 or 4 l h^{-1}.

Although systems should be designed to match the crop water requirements, no detailed experiments have been reported to specify the optimum design or operating conditions for drip irrigation, including fertigation, of coffee. In Zimbabwe, the recommended minimum irrigation interval is about six days. Since coffee is still grown in areas with high rainfall, roots will extend throughout the profile during the rainy season but, possibly, there will be a concentration of feeder roots within the volume of soil wetted by water from each emitter, especially if fertilizer is applied with the water. Gathaara *et al.* (1993), Azizuddin *et al.* (1994) and Ram *et al.* (1992) have reported the results of empirical studies of the use of drip irrigation in coffee in Kenya and in India. In the last paper, the test crop was *C. canephora* and pitcher irrigation (buried water-filled earthenware pots adjacent to each tree), and microsprinklers were also evaluated.

Crops irrigated with drip systems use the same amounts of water as do crops irrigated in other ways. The saving in water comes from more precise applications, providing the system is managed well enough to ensure, for example, that delivery from individual emitters meets the design specifications. This can be difficult in practice. If the soil surface is compact it may be necessary to build a small basin beneath each emitter to allow the water time to infiltrate and to prevent run-off. If cost is a major constraint, a single lateral line can be used to irrigate several rows by moving it from one row to the next, the so-called ‘drag-line’ system. This method is especially useful in young coffee.

Basin irrigation is a traditional method. Water can be applied from a ditch, a hose-pipe connected to a supply line, or from water containers carried into the field. Basins are formed around each tree or group of trees and a measured volume or depth of water applied to each basin. The system can be adapted to supply more than one tree at a time, using multiple outlets. Rates of application from hose-pipes vary between 4 and 20 l min^{-1}. This is a low-cost and efficient way of applying water but, again, it is necessary to ensure that an adequate volume of soil is wetted within the root zone.

As with nearly all crops, no single method of irrigation is necessarily better than another: each can be made to work well. The choice depends on the particular conditions, resources and the priorities of individual growers.

CONCLUSIONS

Water availability plays a dominant role in many aspects of the growth, development and yield of the crop. Despite the increasing international importance of irrigation in commercial coffee production, many of the relationships have not been quantified in commercially useful ways. This is especially surprising in view of the detailed understanding of many aspects of the water relations of the coffee plant, particularly the mechanisms controlling the development of flower buds.

Crop development

- A period of water stress, induced either by dry soil or dry air, is needed to prepare flower buds for blossoming, but the intensity and duration of the stress required have not been specified.
- Blossoming is stimulated by rain (or irrigation).
- Water must be freely available during the period of rapid fruit expansion to ensure large, high-quality seeds.

Plant water relations

- Commercial cultivars have retained characteristics adapted to shady environments.
- High leaf temperatures ($>26°$C), acting alone or together with dry air (saturation deficit >1.6 kPa), induce partial or complete stomatal closure during the day, even when the soil is close to field capacity.
- On sunny days, leaf water potentials (ψL) can be as low as -1.5 MPa, even when the soil is wet, or -2.8 to -3.5 MPa if the soil is dry. Photosynthesis and transpiration rates decline when leaf water potentials fall below about -1.0 MPa.
- Fast rates of transpiration cannot be maintained when the evaporative demand is excessive.

Crop water requirements

- Our understanding of the actual water use of crops grown in diverse ways is imperfect.
- Present methods of estimating crop water requirements for the purposes of irrigation scheme design and management, are imprecise and, probably, subject to large errors depending on local circumstances and the system of irrigation used.

Irrigation

- The need for irrigation, and its role in controlling the timing of flowering, vary depending on the rainfall distribution and the severity of the dry season.
- Two geographic areas, in particular, need to be distinguished; those close to the

equator with a bi-modal rainfall pattern and those at higher latitudes with a single rainy season and a single extended dry season.

- Yield responses to irrigation, and the associated financial benefits, have not yet been adequately described or quantified in ways that are useful to planners and others, in either location.
- Allowable soil water deficits have been specified for only a few situations, usually linked to conventional sprinkler systems of irrigation.
- There is little published information, based on sound experimental work, on how to design and operate advanced drip or micro-jet irrigation systems to best advantage.

Research needs

In order to interpret the role that water plays in the growth and development of the coffee plant, and to apply this scientific understanding to practical advice that can assist the grower to plan and to use water effectively – whether rainfall or irrigation – for the production of reliable, high-quality crops, there is a need to do further research.

- Well designed and managed field experiments should be conducted, over a range of typical sites, to quantify the yield responses of coffee to water. These are likely to vary with cultivar, planting density and soil nutrient status.
- Adequate supporting measurements (crop, soil and prevailing weather conditions) must be taken to allow the results to be interpreted sensibly, and applied with confidence to other locations where the climate and soils may be different.
- Our understanding of the physiology of the coffee plant is such that the development of a process-based model should perhaps precede the experiments in order to set the parameters for the field research and to prioritize the measurements to be taken. For example, it appears that flowering can still be stimulated if only part of the root system is kept dry (Crisosto *et al.* 1992).
- Linked to this is the need to develop further the understanding of the factors influencing the actual rates of water use of coffee, building on the work of Gutierrez and Meinzer (1994a) in Hawaii.
- The design and operating criteria for drip and other appropriate irrigation systems need to be specified with precision in order to optimize crop-yield: water-use efficiencies. Methods of drought mitigation need to be investigated further, including selecting genotypes for drought tolerance.
- By linking the outputs from this research to a geographic information system, a method for assessing the benefits of irrigation, in crop and financial terms, could be developed and used to justify investments in specific locations and farming systems.

The notorious lack of stability in world coffee prices is often caused by fluctuations, real or imaginary, in the predicted production levels. The profitability of coffee growing changes accordingly, and this impacts directly on the economies of individual countries, as well as on the livelihoods of the people involved in its production including smallholders and the employees of large-scale commercial producers. Rainfall variability is one of the principal factors contributing to this instability, but the effects of drought are, as yet, unable to be quantified with precision. Nor is it possible to recommend with confidence where and when irrigation is worthwhile, and how it is best practised. For a commodity crop of such international commercial importance as coffee, and with increasing demands on all fresh water supplies, this is not good enough.

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