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THE WATER RELATIONS AND IRRIGATION REQUIREMENTS OF CASHEW (*ANACARDIUM OCCIDENTALE* L.): A REVIEW

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SUMMARY

The centre of origin of cashew is believed to be Brazil, from where it has spread since the 16th century throughout the tropics. In recent years, Vietnam has surpassed India to become the world's largest producer of cashew nut. Most of the research on the water relations of cashew has been done in Brazil, where it is both a large-scale commercial and a smallholder crop, and in Australia, where cashew is a possible emerging new crop. There are two 'types' of cashew: 'talls' and 'dwarfs'. Both are evergreen trees in which vegetative growth occurs in a series of flushes. Flowers form annually on the end of branches in the dry season, and flowering continues for two to four months. It then takes about two months from pollination for the nut to mature. Roots can extend to great depths (>5 m), while cashew's wide-spreading rooting habit is critical to its successful adaptation to semi-arid/dry conditions. The optimum temperature for CO_2 assimilation is in the range 25–35 °C. Progressive closure of the stomata occurs at saturation deficits of the air >1.5 kPa. In the field, differences in rates of gas exchange between irrigated and unirrigated cashew trees only become apparent three or four months after the end of the rains, the stomata playing an important role in maintaining a favourable leaf water status in dry conditions. Sap flow measurements indicate transpiration rates of 20–28 L d^{-1} $tree^{-1}$. Irrigation can be beneficial during the period from flowering to the start of harvest, but reliable estimates of water productivity have yet to be established. The best/only estimate is 0.26 kg (nut in shell) m^{-3} (irrigation water). There is a continuing need to develop a method to estimate the water requirements of cashew, to identify where and when irrigation of cashew is likely to be justified and to develop a practical irrigation schedule.

INTRODUCTION

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

Cashew is a native of South America with a likely centre of origin in the *cerrados*[2] of central Brazil, or possibly in the coastal zones of north-eastern Brazil since this is

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

where there is the greatest diversity of the *Anacardium* species. Cashew was probably introduced into Africa and India by the Portuguese in the 16th century. It is now found throughout the tropics at latitudes between 27°N (Florida) and 28°S (southern Africa) at altitudes below about 800 m. Cashew is a crop generally associated with coastal regions (Bezerra *et al.*, 2007; Martin *et al.*, 1997; Nair, 2009; Nambiar, 1977, all citing others).

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

The structure of the cashew industry in the principal producing countries has been described by Hall *et al.* (2007). For example, in Vietnam, where the industry has expanded rapidly in recent years (it now produces 32% of the world's crop), the majority of cashew growers are typically smallholders with 2 ha orchards. Similarly, in Tanzania most households have fewer than 100 cashew trees (Martin *et al.*, 1997). By contrast in Brazil, although small and medium size producers are in the majority (in 1995/1996 there were 195,000 farmers growing cashew trees), 32% of the crop is produced on large-scale land holdings (>100 ha; Hall *et al.*, 2007). In India, where cashew is described as 'a poor man's crop but a rich man's food', the cashew industry employs around one million people as labourers, mainly women, to process raw cashew (Nair, 2009). In Brazil, about 280,000 people are employed in cashew cultivation (Amorim *et al.*, 2011).

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

An attempt is made in this paper to review what is known about the water requirements of cashew, and to interpret this research, which was undertaken mainly in Brazil and Australia, in practically useful ways. A similar format to that used in previous reviews in this series, including other crops grown for their fruit, such as banana (Carr, 2009), coconut (Carr, 2011), *Citrus* spp. (Carr, 2012a) and pineapple (Carr, 2012b), is followed. It begins with a description of the stages of crop development (including roots) in relation to water availability, followed by reviews of plant water relations, crop water requirements, water productivity and, finally, irrigation systems.

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

CROP DEVELOPMENT

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

Vegetative

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

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

Under cultivation the number and duration of each phase varies depending on local conditions. As an example, the sequence of the crop development stages that occur in Binh Phoc province in Vietnam, where there is a single rainy season, is summarised. In the case of young cashew trees, vegetative growth occurs in a series of flushes throughout the year. With mature trees, two to three periods of active shoot growth can be identified. The first flush occurs in late April to May, after the harvest has ended, and soon after the start of the rains. This is followed by the second flush in August or early September. The so-called pre-flowering flush occurs in late October and November, at the start of the dry season (Peng *et al.*, 2008).

Flowering

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

Water availability can also influence the relative number of male and hermaphrodite flowers produced. For example, in an irrigation experiment in the Northern Territory of Australia (details below) the irrigated treatment had more male flowers per panicle, in weeks three to seven of the flowering phase, than the unirrigated control treatment (Schaper *et al.*, 1996).

Fruiting

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

An example of the yields that can be achieved when water is not a limiting factor is provided by Silva *et al.* (2004). In north-east Brazil (03°41′S 35°43′W), where there are two well-defined seasons, a rainy season (the mean annual rainfall is 1640 mm) and a dry season that lasts from April to December, a selection of early-dwarf cashew clones were compared in terms of fruit and pedicel (cashew apple) yield over the six years (1990/1991–1995/1996) following field planting in 1990. Initially the tree spacing was 6 × 3 m (555 trees ha^{-1}) but, because there was mutual shading by the end of the third year, the plant density was then reduced to 278 trees ha^{-1} (see below). The trees were drip irrigated daily during the dry season with varying quantities of water depending on the year/stage of crop development. It was a sandy soil. Large yields were already being harvested in the second year. Over five seasons (1991/1992 to 1995/1996) the average number of nut-in-shell (and pedicels) harvested annually was around 250,000 ha^{-1}; yield of nut-in-shell was about 1600 kg ha^{-1} (sun or oven dried), and that of pedicels was close to 17,000 kg ha^{-1} (fresh weight, mostly water). For comparison, the average yield of nut-in-shell in Brazil (from mainly unselected 'talls') is only 140 kg ha^{-1} and in Vietnam 340 kg ha^{-1} (FAOSTAT, 2012). In India, by the year 2000, average yields had reached 865 kg ha^{-1} (Nair, 2009). These figures appear to be realistic.

Plant density

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

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

Roots

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

In his overview report on cashew research in Australia, Grundon (1999) summarised the results of work on roots undertaken by Richards (1993) in the Northern Territory, by J. A. Sherrard and others in Western Australia and north Queensland, and by P. J. O'Farrell in Queensland. This was research that had previously been described mainly in unpublished workshop papers. On sandy red earth soils cashew extracted water from depths of at least 1.8 m, whereas elsewhere on a flood-irrigated clay soil the maximum depth of water extraction was 0.8 m, within a 2.7 m distance from the tree trunk. Again in Australia, the soil water content continually declined down to depths of at least 4.0 m in a deep, sandy soil, suggesting root activity at these depths (Schaper *et al.*, 1996).

Partitioning of dry matter

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

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

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

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

Summary: crop development

1. Vegetative growth occurs in two or three identifiable flushes each year.
2. Flowers form on the end of branches in the dry season: they can be male or hermaphrodite.
3. Flowering continues over a two- to four-month period.
4. The development of the nut takes about two months from pollination.
5. Harvesting extends over 10–12 weeks, preferably when it is dry.
6. Wide tree spacing allows intercropping in the early years: close spacing requires surplus trees to be thinned subsequently in order to minimise water stress.
7. The spreading root habit of cashew is critical in its successful adaptation to dry conditions.
8. Roots can extend to depths of >5 m: water extraction has been monitored down to 4 m.
9. Nut-in-shell and cashew apple together make up less than 10% of the aboveground dry mass of the tree.

PLANT WATER RELATIONS

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

Photosynthesis

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

Further north in Brazil, (3°26′S 39°08′W; alt. 31 m), Lima *et al.* (2010) monitored gas exchange at monthly intervals over a year on leaves exposed to the sun or shaded in a field experiment with mature, dwarf trees. Surprisingly, there were no differences between the irrigated or rain-fed trees in stomatal conductance, transpiration, photosynthesis, internal or external CO_2 concentrations or leaf temperature. There were however differences between sun-exposed and shaded leaves as well as seasonal variability. Both clones (CCP 76 and BRS 189) tested responded in similar ways. Amorim *et al.* (2011) subsequently reported the results of related gas exchange and other measurements made in a similar experiment, again in Brazil (4°10′S 38°27′W: alt. 60 m). These included the recording of soluble carbohydrate, potassium, sodium and chloride ion concentrations. Over the five months of measurement (covering the dry season, total rainfall 17 mm), there was seasonal variation, but once again there were no differences (except for photosynthesis) between the two watering treatments. The only exception was that foliar-N amino solutes and proline were higher in plants grown under rain-fed conditions than in those that were irrigated. Given the short-term nature of the experiment, it is perhaps not surprising that the yield of nuts from these two treatments was similar. It is not very clear what these two experiments tell us about the physiology of cashew, except the relative insensitivity of gas exchange to dry conditions.

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

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

Transpiration

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

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

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

Summary: plant water relations

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

CROP WATER REQUIREMENTS

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

WATER PRODUCTIVTY

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

Brazil

The results of a long-term (1996–2002) irrigation experiment conducted in the north-east of Brazil (3°26′S 39°08′W; alt. 31 m) were reported by Oliveira *et al.* (2006). The climate of this important cashew-growing, predominantly rain-fed area is characterized by a dry season lasting from July to December. The average annual rainfall is about 1000 mm but is very variable (from 600 to 1500 mm during the seven years the experiment covered). The experiment compared the responses of three dwarf genotypes (CCP 09, CCP 76 and CCP 1001, grafted on to seedlings and spaced at 7 × 7 m) to three irrigation regimes, together with an unirrigated control treatment. The soil was described as a deep, sandy red-yellow podzol. Three irrigation frequencies were compared, beginning when the trees were two years old. Trees were irrigated when the cumulative evaporation from a USWB Class A pan reached 10 mm (on average over the seven years this equated to daily irrigation), 30 mm (three-day intervals) and 50 mm (five-day intervals). In order to maintain the soil water potential above −20 kPa in the top 0–0.5 m of the root zone in the wettest (10 mm) treatment, adjustments were made each month based on tensiometer readings. All three irrigation treatments received the same total amount of water over a season. For fully developed trees this totalled 400 to 500 mm each year. Water (with fertilizer) was applied through a single micro-sprinkler per tree. Unirrigated treatments received the same total amount of fertilizer.

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

Australia

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

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

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

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

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

The results of an irrigation experiment with four-year-old trees growing on a clay soil in the Northern Territory, Australia (managed by Richards (1993)) were summarised by Grundon (1999). Yields of nut-in-shell were similar when irrigation was applied after the cumulative evaporation from a USWB Class A pan had reached 150 or 300 mm. But yields declined (fewer nut-in-shell) if irrigation was withheld until cumulative evaporation had reached 600 mm. Reductions in the frequency of irrigation did not affect the depth of water extraction, but the zone of water depletion increased laterally.

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

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

Summary: water productivity

1. In Brazil, irrigation resulted in a cumulative yield benefit of +77% over seven years (above a base yield of 1054 kg ha^{-1}) for two dwarf clones. The third clone yielded more than the other two under dry conditions but gave the same yield as the other two when irrigated.
2. The average water productivity (nut-in-shell) for the two clones that responded to irrigation was about 0.26 kg m^{-3} (irrigation water).
3. The yield increase was due to more, not larger, nuts being harvested.
4. Alternate bearing confounded the evaluation process.
5. In northern Australia, experiments suggested that there was no yield benefit from irrigation before cashew trees flowered.
6. Benefits from irrigation from flowering onwards included larger yields (+43%) as a result of bigger nuts. Kernel recovery was also improved. In contrast to Brazil, the unirrigated trees in Australia had more nuts (+19%) than the irrigated trees (as a result of having fewer male flowers).
7. A linear relationship (slope of line = 6 g m^{-2}) was obtained between the nut yield, expressed on a crop surface area basis, and water applied (irrigation and rainfall). Unfortunately, there is no comparable figure.
8. Cashew can survive for long periods without rain before flowering, but irrigation is beneficial from flowering until harvesting begins. There must be an interaction with plant density, but this does not seem to have been studied.
9. The cashew is notorious for the great variability that exists between trees and even within a single tree, making experimentation difficult (C. P. Topper, personal communication, 2012)

IRRIGATION SYSTEMS

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

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

In Binh Phoc province, Vietnam (11°45′N 106°43′E), the advice is to apply 100 L $tree^{-1}$ once every seven to 10 days during flowering, and 200 L $tree^{-1}$ once every 15 to 20 days during nut setting. The recommendations are based on the results of an irrigation experiment (details were not presented) with six-year-old trees (Peng *et al.*, 2008). These rates are equivalent to 14 or 10 L d^{-1} and 13 or 10 L d^{-1} respectively.

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

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

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

Soil and water conservation

In India, where cashew is grown on the steep slopes of the west coast region, water stress occurs during February to May despite an annual rainfall of 3000–3500 mm (Rejani and Yadukumar, 2010). The period of water stress occurs when the crop is in the flowering and fruit set stages of development. A soil water deficit of up to 300 mm can occur at this time. A number of soil and water conservation techniques were evaluated on a very steep (up to 40%) eroded slope at Puttur over a seven-year period from planting in 2003 up to 2010. Yield and other growth parameters were recorded for five years (2005/2006 to 2009/2010). The two most effective conservation techniques were a 'modified crescent bund' and 'coconut husk burial'. These both reduced runoff from 37% of the annual rainfall (mean total 3011 mm) in the control to 20% and 22% respectively. The amount of eroded soil was reduced by about 50% from 9.7 t ha^{-1} a^{-1} (control) to 4.6 and 4.8 t ha^{-1} a^{-1} in the same two conservation treatments. There was also a yield benefit: total yield of 'nut-in–shell' over the five years was increased by about 33% from 4.9 t ha^{-1} to 6.45 and 6.60 t ha^{-1}. A cost benefit analysis suggested that an investment in conservation measures of the sort described was financially worthwhile. The question remains as to whether farmers perceive the extra work involved to be justified.

CONCLUSIONS

Research on many aspects of cashew nut production is normally undertaken at a national level, although the integrated crop management project in Tanzania is an example of international cooperation (Martin *et al.*, 1997). In the same way, detailed

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studies on the developmental physiology, water relations and irrigation need of this crop are largely confined to Brazil (where the crop is believed to have originated) and Australia (where cashew is still an emerging commercial crop). This is an interesting example of two extreme positions from which to undertake research. As an indigenous species, Brazil has the opportunity to exploit cashew's genetic diversity, and to support a successful commercial sector looking to do even better. In contrast, Australia is looking to establish a new industry, but with little background information from which to work. Very wisely, Australia began the process by establishing a searchable database of the international research literature on cashew (mainly covering the period from 1979 to 1998, both the formally published and the 'grey' literature). This was then reviewed in detail to see what lessons there were for Australia, and to identify the likely limiting factors that needed to be addressed as a priority (Grundon, 2000).

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

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REFERENCES

Amorim, A. V., Gomes-Filho, A., Bezerrs, M. A., Prisco, J. T. and Lacerda, C. F. (2011). Production and physiology of dwarf cashew under rainfed and irrigated conditions. *Brazilian Journal of Agricultural and Environmental Engineering* 15:1014–1020.

Ascenso, J. C. (1986a). Potential of the cashew crop – 1. *Agriculture International* 38:324–327.

Ascenso, J. C. (1986b). Potential of the cashew crop – 2. *Agriculture International* 38:368–371.

Bezerra, M. A., Lacerda, C. F. de, Filho, E. G., Abreu, C. F. B. de and Prisco, J. T. (2007). Physiology of cashew plants grown under adverse conditions. *Brazilian Journal of Plant Physiology* 19(4):449–461.

Blaikie, S. J. and Chacko, E. K. (1998). Sap flow, leaf gas exchange and chlorophyll fluorescence of container-grown cashew (*Anacardium occidentale* L.) trees subjected to repeated cycles of soil drying. *Australian Journal of Experimental Agriculture* 38:305–311.

Blaikie, S. J., Chacko, E. K., Lu, P. and Müller, W. J. (2001). Productivity and water relations of field-grown cashew: a comparison of sprinkler and drip irrigation. *Australian Journal of Experimental Agriculture* 41(5)663–673.

Carr, M. K. V. (2009). The water relations and irrigation requirements of banana (*MUSA SPP.*): a review. *Experimental Agriculture* 45:333–371.

Carr, M. K. V. (2011). The water relations and irrigation requirements of coconut (*Cocos nucifera* L.): a review. *Experimental Agriculture* 47:27–51.

Carr, M. K. V. (2012a). The water relations and irrigation requirements of citrus (*Citrus* Spp.): a review. *Experimental Agriculture* 48:347–377.

Carr, M. K. V. (2012b). The water relations and irrigation requirements of pineapple (*Ananas comosus* var. *comosus*): a review. *Experimental Agriculture* 48(4):488–501.

Dagg, M. and Tapley, R. G. (1967). Cashew nut production in southern Tanzania V – water balance of cashew trees in relation to spacing. *East African Agricultural and Forestry Journal* 33:88–94.

De Souza, R. P., Ribeiro, R. V., Machado, E. C., de Oliveira, R. F. and de Silveira, J. A. G. (2005). Photosynthetic responses of young cashew plants to varying environmental conditions. *Pesquisa Agropecuária Brasileira* 40(8):735–744.

FAOSTAT (2012). Available at: http://faostat.fao.org/site/567/default.aspx#ancor (accessed 30 May 2012).

Grundon, N. J. (1999). *Overview of Australian Cashew Literature*, Technical Report 25/99, CSIRO Land and Water, Atherton, Australia.

Grundon, N. J. (2000). *The Australian Cashew Industry: An Information System*. Rural Industries Research and Development Corporation, Report 00/15, Kingston, ACT, Australia, 182 pp.

Hall, M., Patel, P., Sarmiento, G., Smith, N., Sostowski, A. and Waxman, S. (2007). *Benchmarking the Global Cashew Industry*. Report of Development Alternatives, Inc (DAI). http://sipa.columbia.edu/academics/concentrations/epd/documents/2006-7/Benchmarking%20the%20Brazil%20Cashew%20Sector.pdf (accessed 3 June 2012).

Lima, M. A., Bezerra, M. A., Gomes-Filho, E., Pinto, C. M. and Elias Filho, J. (2010). Gas exchange in leaves of sun and shade of cashew in different water regimes. *Revista Ciencia Agronomica* 41:654–663.

Martin, P. J., Topper, C. P., Bashiru, R. A. *et al.* (1997). Cashew nut production in Tanzania: constraints and progress through integrated crop management. *Crop Protection* 16(1):5–14.

Nair, K. P. P. (2009). The agronomy and economy of some important industrial crops. *Advances in Agronomy* 101:183–312.

Nambiar, M. C. (1977). Cashew. Chapter 17. In *Ecophysiology of Tropical Crops*, 461–478 (Eds P. de T. Alvim and T. T. Kozlowski). New York, NY: Academic Press.

Nambiar, M. C., Rao, B. E. V. V. and Thankamma Pillai, P. K. (1990). Cashew. Chapter 9. In *Fruits: Tropical and Subtropical*, 386–419 (Eds T. K. Bose and S. K. Mitra). Calcutta, India: Naya Prokash.

Northwood, P. J. and Tsakiris, A. (1967). Cashew nut production in southern Tanzania III – early yields from a cashew spacing experiment. *East African Agricultural and Forestry Journal* 33:81–82.

Oliveira, V. H., Miranda, F. R., Lima, R. N. and Cavalcante, R. R. R. (2006). Effect of irrigation frequency on cashew nut yield in northeast Brazil. *Scientia Horticulturae* 108:403–407.

Peng, R., Christian, K., Lan, La, P. and Bihn, N. T. (2008). *Integrated Cashew Improvement Program*. Manual for ICI program trainers and extension officers in Vietnam. Darwin, N.T.: Institute of Agricultural Science for South Vietnam, Charles Darwin University. http://www.card.com.vn/news/Projects/029VIE05/MS9%20Cashew%20ICI%20manual.pdf (accessed 4 June 2012).

Rao, B. E. V. V. (1998). Integrated production practices of cashew in India. Food and Agriculture Organization of the United Nations paper, Rome, Italy. Available at: http://www.fao.org/docrep/005/ac451e/ac451e04.htm (accessed June 2012).

Reddy, S. E. and Reddy, K. S. (1987). Partitioning of nitrogen, phosphorus and potassium in cashew (*Anacardium occidentale* L.) trees. *Indian Cashew Journal* 18:17–21.

Rejani, R. and Yadukumar, N. (2010). Soil and water conservation techniques in cashew grown along steep hill slopes. *Scientia Horticulturae* 126:371–378.

Richards, N. K. (1993). Evolving cashew orchard systems for the Northern Territory. Cashew Research in Northern Territory, Australia, 1987–1991. *Department of Primary Industry and Fisheries Technical Bulletin* No. 202:39–49 (Darwin NT).

Schaper, H. and Chacko, E. K. (1993). Effect of irradiance, leaf age, chlorophyll content and branch-girdling on gas exchange of cashew (*Anacardium occidentale* L. leaves. *Journal of Horticultural Science* 68(4):541–550.

Schaper, H., Chacko, E. K. and Blaikie, S. J. (1996). Effect of irrigation on leaf gas exchange and yield of cashew in northern Australia. *Australian Journal of Experimental Agriculture* 36:861–868.

Sena, J. O. A. de, Zaidan, H. A. and Castro, P. R. de C. (2007). Transpiration and stomatal resistance variations of perennial tree crops under soil water availability conditions and water deficit. *Brazilian Archives of Biology and Technology* 50(2):225–230.

Silva, R. M. B. E., Almeida, F. A. G. and Silva, P. S. L. E. (2004). Peduncle and fruit yield, in six cropping seasons, of early dwarf cashew tree clones irrigated with different water regimes. *Revista Brasileira Frutcultura, Jaboticabal* 26:474–477.

Tsakiris, A. and Northwood, P. J. (1967). Cashew nut production in southern Tanzania IV – the root system of the cashew nut tree. *East African Agricultural and Forestry Journal* 33:83–87.