REVIEW OF MANGO IRRIGATION RESEARCH IN THE NORTHERN TERRITORY

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SUMMARY

Mangoes (*Mangifera indica* L.) are the main horticultural crop in the Northern Territory (NT), grown mainly in the rural areas around Darwin and Katherine. The season's crop in 2009 was around 17 000 tonnes, valued at $46m (Moore 2009). Water use efficiency (WUE) in horticultural production in the NT has become more important as the National Water Initiative leads to water-allocation planning and licensing. Information is required to improve WUE for economic and environmental outcomes. More than 10 studies have been conducted in the NT by the NT Government and CSIRO on irrigation or water use in mangoes. Most NT Government-led research results are presented in annual reports, while those of CSIRO are published in international scientific journals or presented at conference proceedings.

The authors have attempted to present the key results of those studies in this Technical Bulletin. The aim is to provide a single source of information on past research on the use of irrigation in mango production in the NT, to evaluate past work to support improved WUE practices for mango growers and to identify future areas of research with the potential to improve WUE in mango production. It is intended that this information would be useful to those planning research and extension activities in this area and/or to those in need of information on water requirements for mango production.

Studies on mango water use and irrigation covered a number of important areas, including determining pre-harvest irrigation cessation and season-long reduced volume applications on fruit quality; effects of irrigation at different phenological periods, including prior to flowering, and the effects of pre-flowering irrigation on trees receiving flowering-promoting treatments; the effect of age, season and variety on water use as determined by sapflow methods; different irrigation schedules on the efficiency of irrigation water use; and irrigation practices by growers.

Key findings included the following points. Early cessation of irrigation prior to harvest often reduced fruit weight; fruit quality could also be negatively affected by the early cessation of irrigation. Paclobutrazol-treated trees tended to have higher yield if irrigated in the pre-flowering period. Pre-flowering water stress improved flowering and fruit production in non-paclobutrazol treated trees in Darwin. Monitoring at an irrigated site with 2030 L/tree/week applied in October indicated that the volume of water applied exceeded requirements. Water use in mango trees as indicated by sapflow was greater during the wet season. A dendrometer irrigation scheduling method gave a high irrigation efficiency of 77% compared with grower practices or 80% of pan evaporation replacement (31% and 38%, respectively).

The results from some studies were used to provide estimates of WUE (fruit weight kg/m^3 irrigation water) values. High WUE figures (133 and 174 kg/m^3) were achieved with high yields from low irrigation inputs. For example, yields of 62 and 122 kg/tree were achieved with respective inputs of 0.47 and 0.70 m^3/tree. WUE values of less than 10 were related to high irrigation inputs and yields of less than 10 kg/tree. For example, a WUE of 3.1 kg/m^3 from a yield of 7 kg and inputs of 2.26 m^3/tree. These WUE values from experimental data need to be compared with WUE values from current industry practices, but such data is lacking.

Knowledge gaps were identified that require information to support improved WUE practices for mango growers. A number of gaps related to information on mango ecophysiology and water relations. The central gap in this area was knowledge of the crop's water requirements in the NT environment in relation to:

1. Seasonal and environmental conditions.

2. Effects of variety on these requirements.

3. The accuracy of crop factors or coefficients to describe seasonal water use and guide efficient irrigation scheduling.

Major knowledge gaps on yield and timing of production in the NT included:

1. Fruit weight: the effects of season-long deficit irrigation practices on fruit weight in relation to market requirements.

2. Fruit number: the identification of irrigation practices to support optimal fruit numbers in paclobutrazol-treated trees and the relationship between irrigation volume and final fruit numbers for paclobutrazol and non-paclobutrazol treated trees.

3. Fruit quality: the effects of season-long deficit irrigation practices on quality disorders, such as lenticel spotting and post-harvest storability.

4. The effect of irrigation practices and delivery method (drip vs. sprinkler) on vegetative processes, including post-harvest irrigation effects on the earliness of vegetative flushing to assist early flowering.

Additional research gaps included the potential of selected rootstocks to improve WUE and information on mango rooting depth in relation to water uptake.

Information was lacking on a range of non-tree related areas relevant to improving grower management practices and improving WUE. They included the absence of current industry water use benchmarking information, the absence of an evaluation of on-farm deep-drainage, evaporative losses and delivery efficiencies, the absence of soil water availability information to aid scheduling, particularly the frequency of irrigation and the absence of methods to improve delivery efficiencies or reduce losses, such as the use of mulches.

These knowledge gaps need to be addressed. Research will need to be prioritised in line with industry and government priorities.

INTRODUCTION

Irrigators face a changing regulatory environment as management plans and regulations are adapted or introduced that seek to conserve water resources (Pigram 2006). Increasing the efficiency of water use in agriculture in Australia has been identified as one of the major goals necessary to improve the sustainability of Australian agriculture (Khan et al. 2009). The NT is no exception to these trends as water use plans were recently introduced for the Tindall aquifer (Katherine), Alice Springs and Ti Tree that includes licensed allocations for irrigators (Anon 2009b). Water plans will be introduced in future to manage other NT aquifers used by irrigators growing horticultural crops. Mangoes, which are the NT's major horticultural crop, with production exceeding 15 000 tonnes of marketable fruit per annum, are produced using irrigation during the dry season (White 2004; Moore 2009). Hence, mango growers are recognised as major users of water resources.

In order for mango growers to manage their water allocations effectively, sound information is required on the water requirements of mango production in the NT environment and on management strategies to improve water use efficiency. There has been on-going research for over 20 years in the NT on irrigation and water use in mango production, which is now published in NT Government reports, industry and science conference proceedings and international journals.

This Technical Bulletin contains the key results of those studies in a single document, providing a central source of information on mango irrigation research in the NT. It also evaluates past work for information to support improved water use efficiency practices for mango growers and identifies future areas of research to potentially improve water use efficiency in mango production.

BACKGROUND

NT Mango Research

From the 1970s to the 1980s, government research was directed towards identifying the suitability of particular crops, such as mangoes, and develop production systems suitable for the NT environment (Scholefield & Blackburn 1985). That period of research demonstrated a potential for mango production in the NT, including the capability to produce the earliest fruit in Australia (Scholefield & Blackburn 1985; Baker 1986), studies have continued to improve growing systems. Detailed practical guidelines were produced for growers on irrigating mango crops in the NT (Blackburn et al. 1995; Blaikie & Cavanagh 2003; Diczbalis et al. 2006). Those guidelines were based on research conducted by the NT Government or CSIRO, and collaborations between the two, in irrigation and water use by mango trees. Appendix 1 contains current NT Government guidelines.

The Wet Dry Climate and Mango Production

The NT environment differs in rainfall and temperature ranges from some other areas of Australia where mangoes are produced. Mean annual rainfall in Darwin (1.65 m) is higher than in other mango-producing areas, such as Atherton (1.38 m), Bowen (0.84 m), Kununurra (0.84 m) and Broome (0.58 m). Katherine's rainfall (1.12 m) is intermediate between Bowen and Atherton (Baker 1986) (Table 1). Unlike Atherton and Bowen, the Darwin, Katherine and Kununurra areas have a pronounced dry season with little effective rainfall from May to September. At the start of the dry season, mean maximum temperatures are 5 to 8 °C higher in Darwin, Katherine and Kununurra than in Atherton or Bowen. By October and November, mean maximum temperatures in Katherine and Kununurra range from 35.9 to 38.7 °C, which are 4.5 to 5.5 °C higher than in Darwin and close to 10 °C higher than in Atherton. Mean daily minimum temperatures during the coolest period from June to September are 2.5 to 4 °C higher in Darwin than in the next hottest area, which is Kununurra. Darwin is 3 to 6 °C hotter than Katherine during this period.

The NT environment during the dry season could be described as extreme in terms of potential water use by plants, potential evapotranspiration (sum of reference crop transpiration and soil evaporative losses) (Allen et al. 1998), which in northern Australia, may exceed rainfall for up to 10 months of the year (Cook & Heerdegen 2001; Anon 2009c), mostly between April and October (Mollah & Cook 1996; Hutley et al. 2000). This period coincides with flowering and fruit growth in mango trees in the NT (Blaikie et al. 2004). Pan evaporation values in the NT can be considered as high, especially with daily averages approaching 8 mm in September and October (Table 1). The somewhat extreme climate during the dry season coincides with periods with no effective rainfall for approximately four months in Darwin (May-September) and five months in Katherine (May-October). The use of irrigation during this period when there is no rain provides some advantages, since water availability can be closely controlled without having to alter irrigation schedules and strategies. In contrast a number of common soil types used for horticultural production in the NT have high infiltration rates and low levels of moisture retention (Day 1977), which necessitates regular irrigation to maintain soil water levels.

Table 1. Long term monthly and annual rainfall, maximum and minimum mean daily temperatures per month and annual values for Darwin (Darwin airport 1957-2009), Katherine (Katherine Aviation Museum 1999-2009), Atherton (1994-2008), Bowen Airport (1987-2010) and Kununurra (Aero 1986-2010) and mean daily pan evaporation (pan evaporation was available only for Darwin and Katherine) (source BOM)

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Rainfall (mm)													
Darwin	420.3	364.6	320.8	99.8	20.4	2.0	1.3	5.2	15.4	68.7	139	250.4	1707.9
Katherine	267.4	244.9	201.5	38.4	5.2	0.5	1.1	1.8	6.4	33.0	84.6	219.1	1117.1
Atherton	235.1	347.7	224.7	118.7	59.6	42	40	34.5	19.2	35.2	72	150.7	1379.2
Bowen	178.3	242.9	75.7	62.3	44.4	23.9	19.3	22.4	7.2	13.4	35.4	135.1	844.8
Kununurra	198.5	207.5	144.9	26.1	5.7	3.9	1.8	0	3.3	19.3	64	136.2	842.6
Max. (°C)													
Darwin	31.8	31.4	31.9	32.7	32	30.6	30.5	31.3	32.5	33.2	33.3	32.6	32.0
Katherine	34.7	34	34.3	34.2	32.2	30.2	30.4	32.4	35.9	37.8	37.5	36.0	34.1
Atherton	28.4	27.8	26.4	25	23.4	21.5	21.4	22.4	25.6	27.5	28.7	29.0	25.6
Bowen	31.5	31.3	30.9	29.3	27.2	24.9	24.5	25.4	27.4	29.3	30.5	31.4	28.6
Kununurra	35.9	35	35.7	35.4	33	30.3	30.5	32.6	36.6	38.7	39	37.1	35.0
Min.(ºC)													
Darwin	24.8	24.7	24.5	24	22.1	19.9	19.2	20.4	23	24.9	25.4	25.3	23.2
Katherine	24.2	23.9	23.1	20.7	16.7	14	12.8	14.6	20	23.7	24.7	24.6	20.2
Atherton	18.8	19.3	18.3	16.7	14	12.8	10.2	11.1	12.6	15.2	16.7	18.3	15.3
Bowen	23.9	23.9	22.8	20.9	18.1	15.1	13.5	14.3	16.4	19.9	22.2	23.5	19.5
Kununurra	25.1	24.8	24.2	22.1	18.9	16.1	15.1	16.1	20.3	23.7	25.4	25.5	21.4
Pan evap.(mm)													
E_p Darwin	6.0	5.7	5.8	6.4	6.9	6.8	6.8	7.2	7.7	8.0	7.4	6.7	6.8
E_p Kath.	5.3	5.3	5.7	6.3	5.6	4.8	5.4	6.4	7.6	7.9	7.4	6.2	6.2

WATER REQUIREMENTS FOR MANGO PRODUCTION

Leaf water potential studies indicate that mango trees have a degree of drought tolerance (Pongsomboon 1991). However, fruit yields are depressed by water deficits during critical periods of the reproductive cycle (flowering, fruit growth and maturation) impacting on fruit retention and size (Lechaudel & Joas 2007; Schaffer et al. 2009). Recent overseas studies have investigated yield responses in mangoes to irrigation below potential evapotranspiration (ET_P) replacement, also termed reference evapotranspiration (ET_o) (Allen et al. 1998) using a crop coefficient (ET_{crop}/ET_P) of 0.8. Results indicated that the reduced water inputs can still successfully maintain yields (Spreer et al. 2007; da Silva et al. 2009; Spreer et al. 2009) but their effect on mango production in the NT is not clear.

Recommended water requirements for mango production in the NT are based on pan evaporation levels (E_{pan}) and a crop factor (water use/E_{pan}) of 0.7, while the above overseas studies were based on potential evapotranspiration levels (Diczbalis et al. 2006; Spreer et al. 2007; da Silva et al. 2009; Spreer et al. 2009). The NT environment is both hotter and drier than the areas in Brazil and Thailand where reduced irrigation studies on mango production or water use were conducted (Vardavas 1987; Hutley et al. 2000; Spreer et al. 2007; Teixeira et al. 2008; da Silva et al. 2009; Spreer et al. 2009). The mango varieties studied overseas

(Tommy Atkins and Chok Anan) differ from the large canopy but typically low-yielding Kensington Pride that is commonly grown in the NT and other parts of Australia (Bally et al. 2002; Knight et al. 2009).

Currently, it is unclear how overseas findings that demonstrate reduced water inputs can be related to mango orchard irrigation practices in the NT. This is due to differences in climate, variety and the different basis of irrigation scheduling (pan evaporation and potential evapotranspiration). There is also little available information on what irrigation practices are currently in use by NT growers.

WATER RESOURCE MANAGEMENT

Water resources in Australia have come under increasing demand. The NT is no exception as despite high wet season rainfall, dry season irrigation is dependant on finite groundwater resources (Pigram 2006). The topography of the NT is not well suited to dam construction and currently most of the water used for irrigation during the dry season is ground water (Anon 2009c). A water plan has been introduced to manage groundwater resources in the Katherine area (Tindall aquifer), in the Alice Springs region and at Ti-tree (Anon 2009b). More water plans are being developed for the Howard Springs aquifer and for other areas in the NT. The future plans may be based on the Tindall plan.

The introduction of water plans has the potential to change the following irrigation practices in mango orchards:

1. A fixed volume of water (ML/ha/year) is allocated for each horticultural crop type and age of tree crop. For example, two-year-old mango trees are allocated 0.9 ML/ha/year and mature mango trees (7+ years old) are allocated 8.6 ML/ha/year (Anon 2009b).
2. Allocated water that is not used can be traded (with some restrictions) within the same area of the aquifer (Straton et al. 2006a; Anon 2009b).

Prior to the introduction of the Tindall plan, Katherine mango growers had no water restrictions and water trading was not permitted (pers. comm. C. Wicks). These changes have highlighted a need for information to assist mango growers with water management. In particular, practices that improve or maintain mango yield and quality while maintaining or reducing water use are a priority. A simple means of quantifying the relationship between yield and water use is by calculating fruit yield per unit of irrigation water used (kg yield/m^3) (Doorenbos & Kassam 1979). This is referred to as a measure of water use efficiency (WUE). Another common measure is irrigation use efficiency (IUE), which is the volume of water used by a plant or crop per unit of irrigation water supplied.

Achieving an improved WUE in mango production will require an accurate understanding of the relationships between environmental factors and water use at various phenological phases of the crop. This is needed to identify opportunities for water saving and how these relationships are modified by crop management and irrigation technology. Key requirements for growers are:

- Accurate information on mango water requirements to achieve high yields and fruit quality while maximising WUE.
- Strategies to assist with the management and potential brokering of water allocations. The ability to trade water provides an incentive to improve WUE. Strategies need to be developed to improve:
  a. Irrigation scheduling i.e. ensure schedules are matched to tree or crop requirements.
  b. Irrigation methods i.e. ensure the most efficient application method is used.
  c. Soil water or tree monitoring i.e. ensure effective monitoring methods are used that support WUE.

This review will provide initial information towards the development of information and strategies to support improved WUE practices for growers.

PAST RESEARCH

This section provides a description and summary of past research on irrigation in mango orchards in the NT with a focus on key results relating to water requirements and irrigation. A central source of information was the NT Department of Primary Industry and Fisheries (now the Department of Resources) *Technical Annual Reports* and *Technotes*. NT-based studies from other organisations, such as CSIRO, were also included where information was available. In a number of cases, the methods used, the results obtained from studies, or the statistical analysis used, were not presented. Where this was the case, a super script is used as follows: [nm] no methods, [nr] no results, [ns] no statistics, or combinations of these.

IRRIGATION VOLUME AND TIMING

Volume and early irrigation cessation

Work in the mid 1980s estimated water use during peak demand at Berrimah Farm in Darwin (soil type, deep red sandy Kandasol) on large Kensington Pride trees (density of 80 to100 trees/ha and canopy diameter 7 m) (Baker & Kuppelwiesser 1987)[nrs]. A water balance model based on the peak evaporation rates of 8 mm a day and a crop factor or 0.7 calculated the demand in October to be ~2100 L/tree/week. This was tested on four trees and soil moisture levels were evaluated with tensiometers. It was determined that three applications per week were necessary (700 L/ application). Cessation of irrigation for one week dropped soil water levels quickly (35 to 40 cb, tensiometer readings) and in two weeks the top 1 m profile held little water (70 to 80 cb) (Baker & Kuppelwiesser 1987)[nr].

Main findings: Large volume and regular applications (2000 L/week/tree) were required to maintain soil moisture using a water balance model based on peak mean pan evaporation and a crop factor of 0.7. The soil at Berrimah Farm lost water rapidly once irrigation had ceased.

Timing and early cessation

1. The effect of timing of irrigation was first investigated in 1988 (Anon 1988)nms. The highest yield was observed in trees irrigated from flowering (variety not reported and flowering stage not defined) through to harvest. The higher yield in irrigated trees was identified as due to higher fruit retention (Table 2). Irrigated trees retained 33% of fruit compared with 14% in non-irrigated trees. The study did not report if the lower yield in trees in which irrigation had stopped one month prior to harvest was due to reduced fruit weight or reduced fruit number. Anon (1988) reported that an additional study applying the same irrigation treatments, provided similar results and that a fourth treatment of continuous irrigation throughout the dry season gave only a marginal improvement in yields compared with the flowering to harvest treatment.

Table 2. Irrigation (850 L/tree/week) periods and fruit yield from Anon (1988)[nms]

Irrigation treatment	Fruit yield (kg)
No irrigation	23.6
Flowering to harvest	61.8
Flowering to one month prior to harvest	34.5

Main findings: Results suggested that irrigation (850 L/week) from flowering to harvest provided the highest yields and ceasing irrigation one month before harvest reduced yields.

2. A study was conducted over two seasons to investigate timing effects on crop development and yield at Coastal Plains Research Station (CPRS) on Kensington Pride (Kuppelwiesser 1990)ns. At the initiation of irrigation treatments, (as listed in Table 3) irrigated trees received 2300 L over a 12 m2 area to saturate the profile, then 950 L/week over 12 m2. The weekly application resulted in declining soil water levels and in September an additional 2500 L/tree was applied to saturate the soil again (Appendix 2).

The first harvest in 1989 reported no differences between treatments[nrs]. This was attributed to high groundwater levels at CPRS following the 1988-89 wet season, limiting the effects of irrigation.

Groundwater levels were reported to be lower in 1990 and the season was described as a ‘severe dry’. Dry conditions lasted from mid April to the end of October. For this season, fruit-set (percentage of terminals with fruit), tree yield (fruit number and kg/tree) and fruit weights were all higher in irrigated than in non-irrigated trees. No irrigation resulted in the lowest fruit-set. Irrigation from 50% panicle appearance to harvest provided the highest number of fruit per tree and highest total weight of fruit per tree. The longest irrigation period (March to harvest) gave the same number of fruit per tree as the ‘flower to fruit-set’ irrigation, but average fruit weight from the long irrigation period was heavier.

Table 3. Irrigation treatments, volume of irrigation (m^3) and yield components (panicle numbers, fruit-set, fruit number and weight per tree and average fruit weight) for the 1990 harvest of six-year-old Kensington Pride trees (values for five trees per treatment) from Kuppelwiesser (1990)[ns]

Irrigation treatment[1]	Water m^3 /tree	No. panicles per 100 terminals	Fruit-set (%)	No. fruit per tree	Tree fruit yield (kg)	Individual fruit weight (g)
'Dry'[1]	0	63.0	10.0	75	23.8	291
'Flower-fruit set'[1]	15	69.9	31.0	219	86.6	398
'Traditional'[1]	20	62.9	24.6	285	128.0	450
'Wet'[1]	33	67.7	25.8	219	100.4	467

[1]Dry = no irrigation; Flower to fruit-set = from 50% panicle appearance to completion of fruit-set five weeks from harvest; Traditional = from 50% panicle appearance to harvest; Wet = irrigation from March to harvest.

Main findings: Results suggested that early cessation of irrigation reduced fruit weight; irrigation affected fruit number, irrigation that included pre-flowering irrigation ('wet' irrigation from March to harvest) or ceased early (flower to fruit-set) resulted in lower fruit numbers per tree than traditional irrigation (from 50% panicle appearance to harvest).

Volume, timing and interactions with pre-flowering treatments

A series of trials investigated if fruit-set and yield could be improved using pre-flowering irrigation, in conjunction with the use of paclobutrazol over four seasons of trials (Diczbalis & Wicks 1996, 1997; Wicks & Diczbalis 1998; Wicks et al. 1999b).

In these trials, paclobutrazol was applied at the rate of 13 mm/week/tree in year 1 to 25 mm/week/tree in the final year (pers. comm. C. Wicks) to 4.5-year-old trees in December 1994 following pruning. Non-paclobutrazol trees were pruned at the same time and irrigated to provide water at volumes indicated in Tables 4 to 6, from the end of the wet season to late April. Following flowering, the trees were irrigated at 40 mm/tree/week through to harvest. There were six trees per treatment. In the following seasons, the same trees were treated as before.

The effects of pre-flowering irrigation on flowering dates were reported during the initial years of the study. In 1995 non-paclobutrazol-treated trees irrigated at 25, 13 and 0 mm/week had two week earlier flowering (50% flowering on 24, 27 and 24 July, respectively) than non-paclobutrazol-treated trees irrigated with 50 mm/week (7 August) (standard error, one day). In that year all paclobutrazol-treated trees flowered earlier than the non-paclobutrazol-treated trees, regardless of irrigation treatment.

For three seasons, the number of flowering panicles was reported. In non-paclobutrazol-treated trees, those that received 50 mm a week pre-flowering had the lowest number of flowering panicles (Table 4). Pre-flowering irrigation was also reported to have decreased flowering in untreated trees in the 1997 season (Wicks & Diczbalis 1998)[nmrs]. In two of the three years, non-paclobutrazol-treated trees, those receiving 0 mm/week had the highest number of flowering panicles (Table 4). In all years paclobutrazol-treated trees had more flowering panicles.

Table 4. The total number of flowering panicles per tree for the 1995, 1996 and 1998 mango seasons for paclobutrazol (Pac.) and non-paclobutrazol (Nil-Pac.) treated trees under four pre-flowering irrigation treatments

	1995		1996[ns]		1998 [ns]	
Irrigation treatment	**Pac. treated**	**Nil-Pac.**	**Pac. treated**	**Nil-Pac.**	**Pac. treated**	**Nil-Pac.**
50 mm/week	252	48	11.5	0	3	2
25 mm/week	245	134	12.8	1.2	18	3
13 mm/week	186	142	32	1.3	41	5
0 mm/week	148	152	6.8	5.5	9	3

Standard error (SE) for treatment comparisons was 28 for the 1995 data

Results for the percentage fruit-set and fruit number per tree were available for the 1995 season. In non-paclobutrazol-treated trees, the percentage fruit-set irrigated at 50 mm/week was lower than in other irrigation treatments (Table 5). The percentage fruit-set did not differ to the same extent in paclobutrazol-treated trees. This finding was reinforced in later years of the study when paclobutrazol-treated trees usually had more panicles, but did not always have a higher fruit-set (Wicks & Diczbalis 1998)[nrs]. Final fruit numbers for 1995 in non-paclobutrazol-treated trees were highest for those that did not receive any pre-flowering irrigation and lowest for those irrigated at 50 mm/week.

Table 5. Percentage fruit-set and fruit number per tree for the 1995 mango season for paclobutrazol (Pac.) and non-paclobutrazol (Nil-Pac.) treated trees receiving four pre-flowering irrigation treatments

	Fruit-set (%)		Fruit no./tree	
Irrigation treatment	**Pac. treated**	**Nil-Pac.**	**Pac. treated**	**Nil-Pac.**
50 mm/week	23	28	47	13
25 mm/week	31	44	78	58
13 mm/week	22	40	44	59
0 mm/week	29	52	44	76

Standard error (SE) for treatment comparisons was 4.4 for percentage fruit and 11 for fruit number

Non-paclobutrazol-treated trees receiving no pre-flowering irrigation had the highest yields for two years, although differences between yields in 1996 and 1998 were minimal because those were low-yielding seasons (Table 6). In contrast, paclobutrazol-treated trees had highest yields when irrigated pre-flowering (13 or 25 mm/week). Results were not available for all treatments for 1997 but agreed with those of other years (Table 6). Non-paclobutrazol-treated trees that were not irrigated had higher yields (44 kg/tree) than irrigated trees; paclobutrazol-treated trees had the highest yield when irrigated (13 mm/tree, yield 37 kg/tree) (Wicks & Diczbalis 1998)[nrs].

Table 6. Yield (kg/tree) for the 1995, 1996 and 1998 mango season for paclobutrazol (Pac.) and non-paclobutrazol (Nil-Pac.) treated trees receiving four pre-flowering irrigations

	1995		1996		1998	
Irrigation treatment	**Pac. treated**	**Nil-Pac.**	**Pac. treated**	**Nil-Pac.**	**Pac. treated**	**Nil-Pac.**
50 mm/week	23	7	1.1	0	1	1
25 mm/week	38	29	0.7	0.2	11	2
13 mm/week	22	28	7.8	0.2	17	3
0 mm/week	21	37	1.2	1	4	2

Standard error (SE) for treatment comparisons was 5 for 1995 data

Main findings: Yields were variable between seasons but suggested a trend in non-paclobutrazol trees that were irrigated prior to flowering to have lower yields than non-irrigated trees. In contrast, paclobutrazol-treated trees had the highest yields if irrigated at 13 to 25 mm/week prior to flowering.

Pre-flowering irrigation and mango varieties

A CSIRO study evaluated the effects of pre-flowering irrigation (watered to field capacity, daily) compared with water stress (maintenance at ~20% extractable soil water content for two months from early May) in Kensington Pride and Irwin 4.5-year-old trees grown in 200-L drums in Darwin over the 2006 season (Lu & Chacko 2000). A control group of well-watered Nam Doc Mai trees was also included.

Flowering was higher in water-stressed Kensington Pride and Irwin trees. Kensington Pride trees had the strongest response with 80% flowering by mid-June compared with 20% of well-watered Kensington Pride trees. Flowering occurred later in Irwin, but was also higher in water-stressed trees, of which 100% had flowered by mid-September when no well-watered trees had flowered. A week after the initiation of post-flowering irrigation (15 July), all water-stressed Kensington Pride and Irwin trees had flowered. In contrast, 50% and 40%, respectively of Kensington Pride and Irwin trees that had been well-watered, failed to flower. The well-watered Nam Doc Mai trees behaved differently, as all flowered by mid June.

The water-stressed Kensington Pride and Irwin trees had significantly higher flowering intensities than non-stressed trees (Table 7). Approximately 40% of Nam Doc Mai shoots flowered. Yields reflected flowering patterns, with significantly more numbers of large marketable (medium and large) fruit produced on water-stressed Kensington Pride and Irwin trees. Water-stressed Kensington Pride and Irwin trees produced approximately four to eight times more fruit, respectively, than the well-watered trees.

Table 7. Flowering intensities (% of shoots/tree that flowered) in Kensington Pride and Irwin trees following irrigation to field capacity (well watered) compared with water-stressed trees from May to July (from Lu and Chacko 2000)

	Variety	
Irrigation treatment	**Kensington**	**Irwin**
Well-watered	13 a	4 a
Water-stressed	72 b	67 b

Different letters for the same variety indicate a significant ($P < 0.05$) difference.

Temperature data from the trial indicated that flowering in water-stressed Kensington Pride trees occurred before temperatures declined to less than 15 °C. From the high proportion of well- watered trees that did not flower, it was concluded that in the absence of cool temperatures, water stress to induce flowering was important to promote early and intense flowering.

Main findings: Both Kensington Pride and Irwin trees that received pre-flowering water-stress irrigation flowered earlier, had more shoots flowering per tree and produced more marketable fruit than trees irrigated to field capacity during the pre-flowering period.

Pre-flowering irrigation and pre-flowering treatments

A CSIRO study evaluated the effects of pre-flowering irrigation (30 to 46 days before peak flowering) in relation to two flowering treatments: (a) a cincturing/morphactin combination or (b) paclobutrazol (Gonzalez et al. 2004). The study was conducted on five-year-old Kensington Pride trees for three seasons in Darwin.

Whole tree water use as determined by sapflow was greatest in the trees that had received pre-flowering irrigation, both during the pre-flowering irrigation period and for one to two months following flowering, depending on the season. In the trees that were irrigated pre-flowering, the paclobutrazol-treated trees used up to 15 L/day more than the cincture/morphactin-treated trees. Peak water use occurred from about mid August to the first week of September, when sapflow ranged from 35 to 65 L/day, depending on flowering and irrigation treatment.

Not irrigating trees was associated more with variable flowering, rather than reduced flowering. Fruit retention was slightly higher in pre-flowering irrigated trees (22.4%) in comparison to non pre-flowering irrigated trees (18.5%). Early season fruit growth rates were higher in the pre-flowering irrigated trees. In years two and three of the trial, trees with no pre-flowering irrigation had smaller average fruit size (year two 162 g and year three 230 g) at harvest than the trees that had received pre-flowering irrigation (year two 255 g and year three 269 g). The effects of irrigation on yield were variable, with pre-flowering irrigated trees having a lower yield (6 kg) than those not irrigated pre-flowering, in the first season. In the second season, in the cincturing/morphactin-treated trees, non pre-flowering irrigated trees had a lower yield than pre-flowering irrigated trees. In the final season, there was a trend in non-pre-flowering irrigated trees to have lower yields ($p = 0.067$) than pre-flowering irrigated trees.

Irrigation practices also affected vegetative growth. After three years, the trees that had received pre-flowering irrigation had larger trunk circumferences and a greater leaf area (79 cm girth and leaf area index (LAI) of 3.7) than those that did not (72 cm girth and LAI of 2.9).

Main findings: Trees receiving cincturing and morphactin or paclobutrazol flowering treatments have better yields if receiving pre-flowering irrigation.

The Effects of Irrigation on Fruit Dry Matter Content and Harvest Maturity

Early cessation

1. A study in the mid 1980s evaluated the effect of ceasing irrigation in early October, two weeks before harvest on harvest maturity as determined by the percentage of fruit dry matter (DM) (Baker & Kuppelwiesser 1987)nmrs. Prior to ceasing irrigation (2100 L/tree/week in three applications), DM was 12.5%. Within two weeks of ceasing irrigation DM rose to 15.5 %.

Main findings: Results were interpreted to indicate that ceasing irrigation two weeks before harvest did not delay ripening over this period and did not negatively affect the increase in DM content as the fruit ripened.

Timing

2. The effect of three irrigations (Table 3) compared with no irrigation, was studied over six weeks prior to harvest in six-year-old Kensington Pride trees on DM development (Kuppelwiesser 1990)ns. The trees with no irrigation consistently had higher DM levels (~ 2%), on the final sampling date, two days before harvest. The 'flower to fruit-set' irrigated trees had intermediate DM levels, between the non-irrigated (labelled dry on the graph) and wet (March to harvest) irrigated trees (Appendix 2).

Main findings: Non-irrigated trees produced fruit with higher DM levels.

The effect of volume of irrigation and its early cessation on DM

3. The effect of the volume of irrigation and its cessation before harvest on MD levels was investigated in 1992 at two sites (sandy loam and sandy) in Katherine in comprehensive trials (Diczbalis et al. 1993).

Results are available for the sandy loam site (see Table 8). The mean yield in trees receiving the lowest irrigation volume (778 L/tree/week) was 65 kg/tree. This was lower than the 100 kg/tree in trees receiving the highest volume (1944 L/tree/week), due mainly to a lower fruit number per tree (Appendix 3). Yield and fruit numbers per tree in the intermediate treatment trees were inconsistent, which appeared to indicate the effects of variability in fruit number per tree rather than the effects of irrigation on fruit number per tree. Cessation timing of irrigation had no effect on tree yield or fruit number per tree (Appendix 3). However, fruit weight was reduced by irrigation cessation four weeks prior to harvest compared with two weeks, one week or no cessation (Table 8). Soil water levels under the different application rates did not appear to differ strongly over the trial period, but the cessation of irrigation resulted in a rapid decline in soil water levels (Appendix 3).

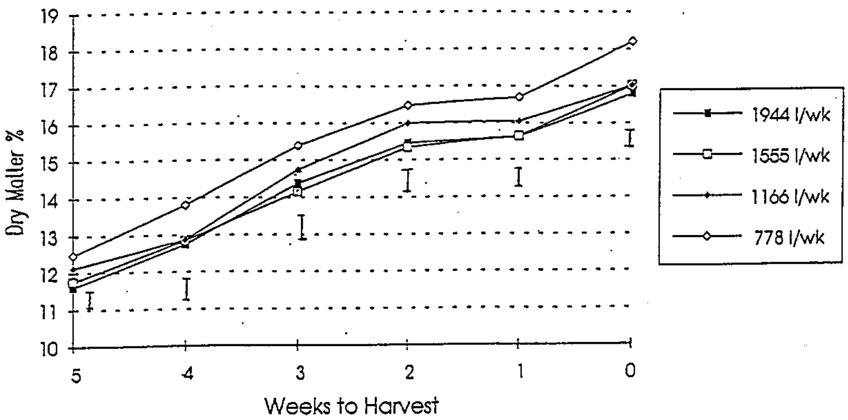
The results from the second site with a sandy soil were similar to those at the sandy-loam site, with the exception that the effects of the cessation of irrigation were greater on the sandy site. The fruit of trees which had irrigation stopped three and two weeks before harvest was 45 g lighter than the fruit of trees which had continuous irrigation (data not presented).

Table 8. Fruit size (g/fruit) in relation to irrigation volume and cessation timing in eight-year-old Kensington Pride trees on a sandy loam, canopy cover of 60%, irrigated three times a week, at Manbulloo in Katherine (Diczbalis 1993)

	Cease irrigation, weeks before harvest				
Irrigation volume pan evaporation	**4**	**2**	**1**	**0**	**mean**
74% (1944 L/tree/week)	304	314	313	309	310a
59% (1555 L/tree/week)	294	321	330	324	317a
44% (1166 L/tree/week)	286	312	317	317	308a
30% (778) L/tree/week)	290	308	320	314	308a
Mean	293a	314b	320b	316b	

Fruit DM levels were affected by both irrigation volume and the early cessation of irrigation (Figure 2). Fruit from trees irrigated at 778 L/tree/week (driest treatment) had reached a 14% threshold approximately one week earlier than fruit from trees receiving other irrigation volumes. In fruit from this treatment, DM levels were highest two weeks after the four-week cut-off had been initiated. Fruit from trees with no cut-off (irrigated to harvest) consistently had the lowest DM levels. However, at three weeks prior to the final harvest date all fruit had DM content greater than 14%.

Irrigation volume and timing of irrigation cessation did not appear to affect fruit brix levels one week after harvest (Appendix 3).



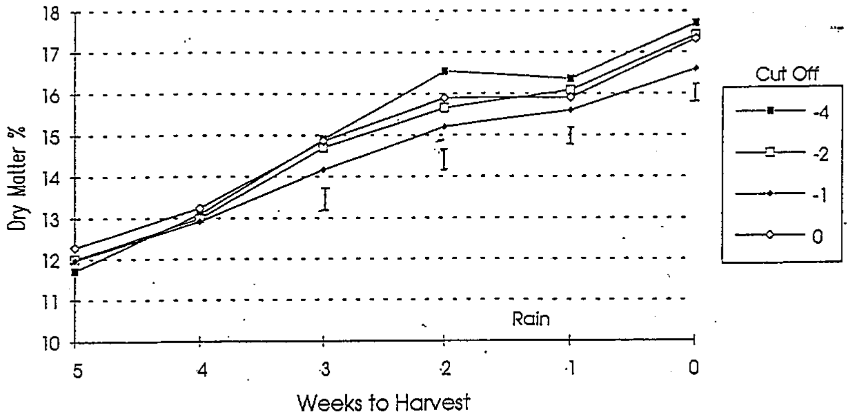


Figure 2. Dry matter (%) in fruit samples from five weeks before harvest, at four irrigation rates (top graph) and four irrigation cut-off timings in weeks before the final harvest (bottom graph) 1992 season at Manballoo on a sandy loam soil with eight-year-old trees (Diczbalis et al. 1993). Vertical bars indicate LSD ($P \leq 0.05$) at each date.

Main findings: the study concluded that DM was affected by irrigation; low volumes or early cessation led to higher FDM levels, indicating earlier maturation. However, there was a trade-off between earlier market maturity (14% DM) and fruit weight, where fruit weight was reduced by ceasing irrigation four weeks before harvest. This effect was more pronounced at the sandy site where fruit size was reduced by 45 g in trees when irrigation was ceased three or two weeks before harvest, which was probably due to less soil water storage capacity. The study also noted that some aspects of fruit quality with reduced irrigation needed further investigation, such as skin and flesh colour; appearance may have been negatively affected.

4. The effect of irrigation volume and timing of irrigation cessation before harvest on DM development, fruit ripening and quality characteristics, was further investigated in 1993 in Katherine (Diczbalis 1994b; Diczbalis et al. 1995a).

Nine-year-old Kensington Pride trees on a sandy loam received four irrigation volumes and irrigation cessation timings (as listed in Table 9). In that trial, the fruit DM from trees irrigated at 40% and 60% of pan evaporation reached 14% three to six days before that from trees on higher irrigation levels (Figure 3). Fruit from trees irrigated at 40% and 60% of pan evaporation also had fruit which was 40 to 50 g lighter than that from trees on the higher irrigation rates (Table 8). Fruit from trees where irrigation ceased four weeks before harvest was also ~ 40 g lighter than fruit from trees that had irrigation stopped one or two weeks before harvest (Table 9).

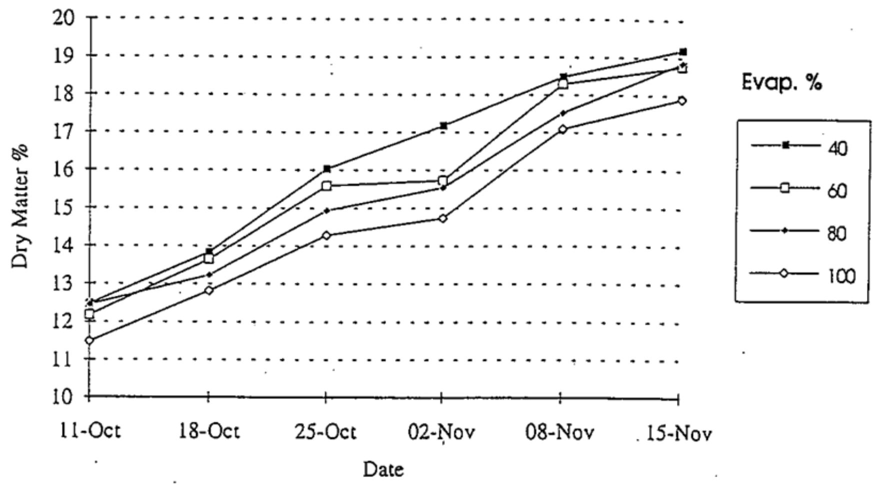


Figure 3. Fruit dry matter (%) from five weeks up to harvest at four irrigation volumes (evaporation replacement, 40%, 60%, 80% and 100%) for the 1993 season at Manballoo, on a sandy loam with nine-year-old trees (Diczbalis 1994b)

Although average fruit weight was lower in the 40% and 60% replacement volumes, fruit numbers per tree were variable and were not related to irrigation treatments and had no significant effect on total yield per tree (Diczbalis et al. 1995a).

Fruit quality in the low irrigation treatment (40% pan evaporation) showed delayed peel colour development compared with the 100% pan evaporation replacement, but there was no consistent effect of irrigation treatment on the number of days to eating ripe (Appendix 4). In both irrigation treatments there was a sharp decline in the number of days to eating ripe from between 76 and 84 days after panicle emergence. This qualitative change could also be expressed in a reduction (from ~16 to 11 days) in the number of days to soft ripe from between 62 and 69 days after 50% anthesis (Appendix 4). Days to soft ripe was identified as a useful maturity guide. Reduced irrigation also increased the level of total soluble solids, which were correlated with DM levels (Diczbalis et al. 1995a). In addition, DM at harvest had a strong and positive relationship (r^2 = 0.88) with fruit brix levels (Diczbalis et al. 1995a).

Table 9. Fruit size (g/fruit) in relation to irrigation volume and cessation timing (weeks before harvest) (Diczbalis 1994b)

	Cease irrigation, weeks before harvest				
Irrigation volume of pan evaporation	**4**	**2**	**1**	**0**	**mean**
100% (2400 L/tree/week)	498.4	515.9	473.7	496.7	496.1b
80% (1920 L/tree/week)	434.6	542.9	534.4	486.6	499.6b
60% (1440 L/tree/week)	413.7	437.5	491.4	498.9	460.4a
40% (960 L/tree/week)	434.7	441.6	485.1	426.7	447.0a
Mean	445.3a	484.5b	496.1b	477.2ab	

Main findings: Diczbalis (1993) observed that fruit forced to reach an DM of 14% by deficit irrigation tended to be of lower quality, particularly if picked at that time. Results from the second trial also showed that reduced irrigation could be used to produce fruit with a higher dry matter, but this was at the expense of a number of fruit qualities, such as colour and size (Diczbalis 1994b; Diczbalis et al. 1995a). It was recommended that growers intending to market high quality fruit should consider irrigating at levels above 70% of pan evaporation and allowing DM to reach 15% before harvest.

Grower Irrigation Practices

1991 survey

1. A survey was conducted in the NT in 1991 of 45 orchards, 19 of which grew mangoes only (Kulkarni & Landon-Lane 1991). Information was provided by growers on some irrigation practices, in which timing varied. The largest proportion of orchards irrigated from flowering to harvest (55%), others irrigated from flowering to two to six weeks before harvest (24%), some irrigated from flowering to one week before harvest (14%) and a few from fruit-set to harvest (7%). The volume of water applied varied between growers (Table 10). It was noted that some growers had adopted low rates to improve fruit quality or reduce vegetative growth. For the upper bound of each irrigation volume category, a ten-year-old tree would have received between 1000 L and 4000 L per week.

Table 10. The proportion of orchards in five irrigation volume categories - water applied/week/tree/year of age (Kulkarni & Landon-Lane 1991)

Irrigation volume in L/week/tree/year of age	Orchards (%)
1-100	22
101-200	16
201-300	6
301-400	22
> 400	7
Unspecified	18

Darwin study

2. A study was conducted on the soil-water status of five-year-old Kensington Pride trees (200 trees/ha, spacing 10*5 m, canopy cover 75%) on a commercial orchard in Darwin from 1991 to 1992 (Diczbalis & Bowman 1991, 1992). The irrigation schedule and soil water results of the study are presented in Appendix 5. The key findings were:

- After the initial watering following flowering, water use by the trees was low, resulting in high soil moisture levels.
- An increase in water use was observed in late August when application rates were 761 L/tree/week, probably during the mid-late fruit fill period.
- An increase in irrigation volume in early September to 1015 L/tree/week did not lead to drainage below the 800 mm profile. Prior to the September irrigation, the tension at 800 mm had increased to exceed 300 millibars during the previous two weeks. The greater tensions at 800 mm indicated greater tree-water and/or environmental evaporative requirements during this period.
- An increase in the weekly irrigation volume to 2030 L/week/tree in October resulted in soil water levels approaching saturation at 40 to 50 mm, with probable drainage occurring past the 1200 mm profile.
- The period when irrigation inputs were determined to be meeting tree requirements (12 to 30 September) was used to evaluate a crop factor. The factor was calculated from the percentage of water used relative to pan evaporation losses (based on mean daily evaporation for Darwin), which gave a crop factor value of 0.47.

Main findings: Initial water requirements following flowering appeared to be low; then water requirements increased in late August and September. However, increased irrigation in October to 2030 L/tree/week delivered excess water.

A second Darwin study

3. An investigation was conducted in the Darwin region over three seasons in a number of mango orchards on soil water status (rainfall, irrigation inputs) and air temperature in relation to phenology (time of flushing, fruit-set and harvest) (Diczbalis et al. 1995b). From that study a number of critical observations were made regarding irrigation practices. Results from a representative farm are presented in Appendix 6. Relevant observations included that:

- At that site, soil moisture levels fell soon after the end of the wet season, with most of the soil moisture in the top 1.2 m being used within four weeks.
- Irrigation amounts during fruit development were considered to be generally higher than required, with two out of three orchards delivering 100 mm/week, when 50 mm/week was considered more than sufficient. For a tree with a canopy of 20 m^2 it was estimated that 100 mm/week was equivalent to 2000 L/week and 50 mm equivalent to 1000 L/week.

Main findings: Within a month of the wet season, soil water levels were low; during fruit development, irrigation at 50 mm/week was considered more than sufficient for the study sites.

WATER USE IN MANGO TREES DETERMINED BY SAPFLOW

A series of studies were conducted by Dr. Ping Lu and others at CSIRO using a Grainer system to quantify sapflow in mango trees in the NT (Lu et al. 2000; Lu 2002, 2005). The level of sapflow provided a measure of tree water use for transpiration and hence could be used as a guide to improve irrigation scheduling. Studies on 13-year-old Kensington Pride trees near Darwin showed total sapflows of 95 to 170 kg/day in mid November under non-limiting soil water conditions, equivalent to a water loss of 140 L/day based on soil water measurements from the site (Lu et al. 2000) (pers. comm. Dr. P. Lu).

Lu (2002)[ns] published a series of weekly sapflow values. Water use was higher in the wet season than in the dry season (Table 11). Because these values represent only water loss from the canopy, it was recommended that the values be multiplied by a factor of about 1.3 to take account of water losses from wind, evaporation, deep drainage and surface run-off.

Table 11. Weekly sapflow (L/week/tree) in trees of different varieties or ages

			Whole plant sapflow (L/week/tree)	
Variety	**Age (years)**	**Trunk diameter (cm)**	**Dry season (well-watered)**	**Wet season (sunny days)**
Kensington Pride	3-4	6	70-84	-
Kensington Pride	6-7	15	245-350	-
Kensington Pride	10-12	23-35	630-700	840-1050
Irwin	10-12	20-24	420-490	630-700
Nam Dok Mai	10	22	560	700-840

The sapflow was measured with a Grainer system in the dry and wet season in Darwin (Lu 2000)[ns]

Container-grown Kensington Pride and Irwin trees were compared for levels of sapflow after periods of water stress. The level of sapflow in water-stressed Kensington Pride trees was approximately 50% of that in water-stressed Irwin trees. In field trials on a soil with a high water- holding capacity, daily sapflow declined to 85% of the control when volumetric soil moisture fell below 15% (Lu 2002).

The sapflow technique was used in further studies to compare how efficient different irrigation regimes were. A comparison was made between three irrigation schedules based on 80% of pan evaporation, a grower's soil-water-based schedule and a twig dendrometer. Results indicated that the plant-based dendrometer gave the highest irrigation efficiency (77% of irrigation water used by the plant) (Table 12) (Lu 2005)[ns]. The grower method based on soil-water readings (capacitance probe) appeared to be slightly more irrigation efficient than the 80% of pan evaporation schedule.

Table 12. Performance of three irrigation schedules: control (80% pan evaporation replacement), grower (irrigation schedule based on capacitance probe) and dendrometer (micro-dendrometer twig diameter readings to indicate irrigation requirements) in a mango orchard, from Lu (2005)[ns]

Irrigation schedule	Irrigation (L/day/tree)	Water used (L/day/tree)	Yield (kg/tree)	Irrigation efficiency (%)
Control	170	53	64	31
Grower	125	47	60	38
Dendrometer	79	61	58	77

Environmental and Seasonal Responses of Mango Trees in Darwin

In a comparison conducted in Darwin over the wet-dry season between five varieties (Strawberry, Haden, Tommy Atkins, Irwin and Kensington Pride), all indicated similarly high net photosynthesis rates during the wet season (peak in March, 14-17 A_{net} mol/m^2/s) (Lu 2005). However, during the dry season, Kensington Pride had the lowest net photosynthesis of all the varieties. As part of that study, the effect of increasing vapour pressure deficit during the dry season and of irrigating trees well during the dry season was observed in Kensington Pride and Irwin (Lu 2005; Schaffer et al. 2009). Kensington Pride trees had the largest decline in stomatal conductance with increasing leaf to air-vapour pressure deficit conditions. These studies indicate that photosynthetic activity in Kensington Pride will be negatively affected by dry atmospheric conditions despite adequate soil water levels.

Application Method

Drip irrigation

A study was initiated in 1997 to compare drip (single emitter per tree) with sprinkler irrigation on newly-established mango seedlings. Drip irrigation was of interest because some growers were using it (Wicks & Diczbalis 1997). Drip irrigation was identified as a method by which growers may reduce water inputs during mango seedling establishment, as drippers have the ability to deliver water more accurately to young trees with a small root zone.

Two years after initiation, growth was not reported to have differed between drip and sprinkler- irrigated trees and that sprinkler-irrigated trees had received ~ 20% more water than the drip irrigated (Wicks et al. 1999a)[nrs].

ESTIMATION OF WATER USE FROM IRRIGATION TRIALS

The irrigation studies in the NT reported here provided an opportunity to estimate total water use for a number of different durations and delivery volumes. Where tree density information was not available, delivery rates for 100, 150 and 200 trees/ha were calculated in ML (Table 13). No studies of post-harvest irrigation practices are available to provide similar figures. The study of Kuppelwiesser (1990) had a 10 x 10 m tree spacing and total delivery ranged from 1.37 to 3.33 ML/ha. For values based on estimated tree densities, the total delivery ranged from 0.47 to 2.30 ML/ha for 100 trees/ha and 0.93 to 4.60 ML/ha for 200 trees/ha. The lowest application rates were for a 30% evaporation replacement rate (778 L/tree/week) with irrigation also ceasing one month before harvest and the highest were for trees irrigated at 50 mm/week for 11 weeks prior to flowering.

WUE had a large range of values. High WUE figures (133 and 174 kg/m^3) were achieved with high yields from low irrigation inputs. For example, yields of 62 and 122 kg/tree were achieved with respective inputs of 0.47 and 0.70 m^3/tree for low evaporation replacement treatments and where irrigation had ceased one month prior to harvest (Diczbalis et al. 1993). WUE values of less than 10 were related to high irrigation inputs and yields of fewer than 10 kg/tree. For example, a WUE of 3.1 kg/m^3 from a yield of 7 kg and inputs of 2.26 m^3/tree (Diczbalis & Wicks 1996).

Table 13. Total water applications per tree in four NT studies including ML/ha and WUE efficiency (yield/m^3 of irrigation), CO = cut off

						ML/ha applied			
Study	**Treatment**	**L/week/ tree**	**Duration (weeks)**	**L/tree applied**	**Fruit yield (kg/tree)**	**100 trees/ha**	**150 trees/ha**	**200 trees/ha**	**WUE kg/m^3**
Anon (1988)									
	Flower to one month before harvest	850	11.5[1]	9775	34.5	0.98[2]	1.47[2]	1.96	35.29
	Flower to harvest	850	15.5[1]	13175	61.8	1.32	1.98	2.64	46.91
Kuppelwiesser (1990)									
	'Flower to fruit-set' 21 July -21 Sept	950	9	13255[3]	86.6	1.33[4]	-	-	65.33
	'Traditional' 21 July -26 Oct	950	14	18005[3]	128.0	1.80[4]	-	-	71.09
	'Wet' 15 March-26 Oct	950	30	33300[3]	100.4	3.33[4]	-	-	30.15
Diczbalis & Wicks (1996)									
+ Pac.	Pre-flow 0 mm/week	0/800	0 + 15[5]	12000[6]	21.0	1.20[2]	1.80	2.40	17.50
+ Pac.	Pre-flow 13 mm/week	260/800	11 +15	14860	22.0	1.49	2.23	2.97	14.80
+ Pac.	Pre-flow 25 mm/week	500/800	11 +15	17500	38.0	1.75	2.63	3.50	21.71
+ Pac.	Pre-flow 50 mm/week	1000/800	11 +15	23000	23.0	2.30	3.45	4.60	10.00
- Pac.	Pre-flow 0 mm/week	0/800	0 + 15	11600	37.0	1.16	1.74	2.32	31.90
- Pac.	Pre-flow 13 mm/week	260/800	11 +14.5	14460	28.0	1.45	2.17	2.89	19.36
- Pac.	Pre-flow 25 mm/week	500/800	11 +14.5	17100	29.0	1.71	2.57	3.42	16.96
- Pac.	Pre-flow 50 mm/week	1000/800	11 +14.5	22600	7.0	2.26	3.39	4.52	3.10
Diczbalis et al (1993)									
	30% replace 0 wk CO	778	10[7]	7780	52.5	0.78[2]	1.17	1.56	67.48
	44% replace 0 wk CO	1166	10	11660	90.2	1.17	1.75	2.33	77.36
	59% replace 0 wk CO	1555	10	15550	95.2	1.56	2.33	3.11	61.22
	74% replace 0 wk CO	1944	10	19440	101.0	1.94	2.92	3.89	51.95
	30% replace four wk CO	778	6	4668	62.1	0.47	0.70	0.93	133.03
	44% replace 4 wk CO	1166	6	6996	122.0	0.70	1.05	1.40	174.39
	59% replace 4 wk CO	1555	6	9330	81.9	0.93	1.40	1.87	87.78
	74% replace 4 wk CO	1944	6	11664	78.3	1.17	1.75	2.33	67.13

[1]15.5 weeks from flower to harvest based on 10 year averages, [2]No tree spacing reported, ML for densities of 100, 150 and 200 trees/ha calculated, [3]Includes the total 4800 L/tree for wet up and top up, [4]Tree spacing was 10 x 10 m, no calculations for higher densities [5]Used 11 weeks (last week of April to mid July) for pre-flowering irrigation duration and 15 and 14.5 weeks for fruit growth irrigation based on 10 year averages for this flowering date, [6]assumed canopy area of 20 m^2 for L/tree rates, [7]10 weeks from flower to harvest based on 10 year averages.

DISCUSSION

This discussion compares the results from the mango irrigation and water use studies in the NT with those from major national and international studies to identify information that will support improved WUE practices for mango growers in the NT and highlight areas for future research to improve WUE in local mango production.

Two broad areas are addressed. The first includes factors related to mango ecophysiology and water relations for crop production. The second includes non-tree factors associated with on-farm management practices. Although the two areas are presented separately, it is acknowledged that they are interrelated.

MANGO ECOPHYSIOLOGY AND WATER RELATIONS FOR CROP PRODUCTION

This section discusses the effects of irrigation on mango fruit yield, vegetative growth in trees, seasonal water requirements, the use of crop factors and coefficients to represent requirements, and the potential role of rootstocks in WUE. Gross fruit yield (kg/tree) consists of two components, the number of fruits per tree and the weight of individual fruits. Fruit quality is also an important qualitative component.

Fruit weight

The effect of early cessation of irrigation on fruit weight appears to be relatively straight forward. In a study in the NT, a relatively large effect was reported on fruit weight when irrigation was ceased two to three weeks before harvest, with average individual fruit weight reduced by 45 g at a site with a sandy soil (Diczbalis et al. 1993). In a similar study on a loam, ceasing irrigation four weeks prior to harvest reduced fruit weights by 35 and 50 g, respectively compared with fruit from trees irrigated up to two or one week before harvest (Diczbalis 1994a). Fruit were also 52 to 69 g lighter from trees that had ceased irrigation five weeks before harvest (Kuppelwiesser 1990). Similarly, in Kensington Pride trees in Bowen, cutting off irrigation 7.5 weeks before harvest significantly reduced fruit weights (individual weight 350 g) compared with 479 and 513 g, respectively for fruit from trees irrigated until 1.5 weeks before harvest or irrigated up to harvest (Simmons et al. 1998). Although an analysis of cell numbers in fruit from these three treatments indicated no significant differences, fruit that suffered from an early water stress period (no irrigation from flowering to 12 weeks before harvest when irrigation was resumed) had fewer cells (Simmons et al. 1998). However, reduced fruit weights following an early cessation of irrigation are due mainly to reduced fruit fill, rather than to fewer cell numbers.

Studies to date indicate that cessation of irrigation one to two weeks before harvest may not reduce fruit weight. However, environmental and soil factors may accentuate the effects of irrigation cessation on fruit weight. The high porosity and low water-holding capacity of a number of NT soils, such as the Kandosol type referred to as a Blain, may accentuate early irrigation cessation effects on fruit size, especially on soils that dry out rapidly (Day 1977; Diczbalis & Bowman 1991; Diczbalis et al. 1995b). In addition, the early cessation of irrigation for up to a month prior to harvest, depending on the flowering date of the crop, may occur during months when pan evaporation values are at a peak (Table 1; Appendix 7). Thus environmental demands at particular times may contribute to reduced fruit fill and hence reduced fruit weights.

Effects of reduced season-long irrigation studies (as opposed to irrigation cut-off studies) in the NT demonstrated inconsistent effects on fruit weight. Reduced irrigation inputs (74%, 59%, 44% and 30% in 1992 and 100%, 80%, 60% and 40% of pan evaporation in 1993) had no significant effect on fruit size in the 1992 season, but in 1993 fruit was 36 g to 49 g lighter after irrigation at 60% and 40% of pan evaporation (Diczbalis et al. 1993; Diczbalis 1994b). Given the large differences in irrigation volumes between treatments, the results suggest that season-long deficits have a small effect on fruit weight. A similar finding was reported in a study in La Reunion that evaluated mild water deficits from one month after flowering compared with fully irrigated trees (Lechaudel et al. 2005). In that study, fruit fresh weight was not significantly affected by water deficits. In a study in Thailand, the weight of fruit from trees receiving irrigation at 50% of potential evapotranspiration (ET_P) was significantly lighter (95 g) than fruit from trees receiving 100 % of ET_P in only one of three years (Spreer et al. 2009) (Appendix 8). In that study, fruit size distribution was affected by reduced irrigation; trees receiving partial root zone deficit (PRD) irrigation (50% of potential evapotranspiration delivered to alternate sides of the tree) had the highest proportion of large fruit in one year only (Spreer et al. 2009). In other studies, reduced irrigation was associated with non-significant trends in reduced fruit weight (Chandel & Singh 1992; Kumar et al. 2008).

Fruit weight is directly related to fruit size. The manipulation of fruit weight by such practices as irrigation can have important effects on market prices of mangoes by affecting size class of the fruit. Analysis of the effects of increasing fruit size by two classes found that the internal rate of return of an NT orchard could be improved by 2% based on market prices in the late 1990s (Ngo 1997). Where markets value larger fruit, irrigation practices may be important to achieve targeted size classes.

The results of overseas and NT studies on mango fruit weight demonstrate some tolerance to reduced season-long irrigation volumes, but not to early cessation (if three or more weeks before harvest). The results of the cut-off studies implied that irrigation during the period of fruit fill from 7.5 to four weeks before harvest, or two to three weeks on sandy soils, was important for final fruit weight (Diczbalis et al. 1993; Diczbalis 1994b; Simmons et al. 1998). However, a number of areas remain unclear, as reductions in fruit weight were recorded with reduced season-long irrigation in some seasons (Diczbalis 1994b; Spreer et al. 2009). It is unclear from reduced season-long volumes of irrigation studies:

1. If reduced fruit weights following reduced season-long volume irrigation in some seasons are the result of a reduced late season fruit fill or are due to a smaller initial fruit size due to reduced cell numbers during fruit development.

2. What environmental factors contribute to lighter fruit in some seasons following reduced season-long irrigation.

3. The effects of reduced season-long rates of irrigation on fruit size distribution, particularly in Kensington Pride mangoes in Australia.

4. If reduced season-long rates of irrigation and the early cessation of irrigation affect fruit weight and how accurately can irrigation be managed to match final fruit weight and hence size to meet market requirements.

Fruit number

The effect of irrigation on fruit number is more complex than on fruit weight. Analysis of mango yield components identified that gross yields (kg/tree) are more affected by fruit number than fruit weight as the fruit number is the most variable of these components (Bally et al. 2002; Spreer et al. 2009).

The level of irrigation has been positively associated with final fruit number in several studies. The level of irrigation during fruit-set was important for final fruit number (Bhambid et al. 1988) and comparisons of reduced season-long volume irrigation over the fruit growth period reported higher fruit retention by trees irrigated at 20% or 40% available soil moisture (ASM) depletion levels than trees irrigated at 60% ASM (Chandel & Singh 1992). Fruit-set and final fruit number were also higher in trees maintained at tensions of -10 to -20 kPa, than at -20 to -30 or -50 to -60 kPa (Singh et al. 2003). Studies in the NT also reported increased fruit-set in trees irrigated following flowering compared with non-irrigated trees (Anon 1988; Kuppelwiesser 1990). In the studies of Diczbalis et al. (1993, 1994) different irrigation volumes had unclear effects on fruit number with variable fruit numbers reported in 1994. In 1993, the results were also mixed but less fruit (more than 100 fewer fruit/tree) occurred in trees receiving 30% evaporation replacement irrigation than 44% and 74% evaporation replacement.

Diczbalis et al. (1993, 1994) noted that mango fruit numbers were variable between treatments. These results indicate that experiments with the analytical power to tolerate a high degree of tree to tree variability may be needed to quantify the effects of irrigation on mango fruit numbers. Fruit numbers per tree in the NT environment can be quite variable. For example, in a three-year study on Kensington Pride trees (Gonzalez et al. 2004), the effect of within treatment tree to tree variability was larger than the treatment effect. This may be due to the effects of the environment on the number of flowering terminals per tree, in addition to variation in fruit-set per panicle (Davenport 2007).

Reduced irrigation volume studies also provide some evidence of a negative response to high irrigation volumes on fruit number, following positive effects at lower irrigation rates. Negative yield responses to over-irrigation are cited for a number of crops (Geerts & Raes 2009). In a mulch and irrigation study, final fruit numbers in mango trees receiving 50% pan evaporation replacement irrigation were significantly higher (by 40 to 130 fruit/tree) than trees receiving 25% or 75% evaporation replacement irrigation in three of five years; for each of the five years, 50% pan evaporation replacement resulted in the largest fruit number (Kumar et al. 2008). Fruit yields (kg/tree) were also higher in each year in trees receiving 50% rather than 75% pan evaporation replacement irrigation. However, this difference was not significant (Kumar et al. 2008). In a Brazilian study, trees receiving 100% potential evapotranspiration replacement had 2 to 3 t/ha lower yields than trees irrigated at 70%, 80% or 90% potential evapotranspiration replacement (da Silva et al. 2009) (Appendix 8). The lower yields at the highest irrigation rate were due to both reduced fruit number and reduced fruit size (pers. comm. da Silva).

The timing of irrigation can negatively affect fruit-set and fruit numbers per tree. For example, in an NT study, the proportion of fruit-set was significantly and negatively reduced by pre-flowering irrigation in non-paclobutrazol-treated trees at both low and high rates (e.g. 13 and 50 mm/week) (Diczbalis & Wicks 1996). Another Darwin-based study found that irrigation of both Kensington Pride and Irwin trees (non-paclobutrazol-treated) to field capacity during the pre-flowering period led to later and significantly lower flowering intensities and fruit number compared with water- stressed trees (Lu & Chacko 2000). A study in Queensland also found that pre-flower droughting of non-paclobutrazol-treated trees improved the number of terminals that flowered and tree yields were increased in two of three seasons (Bally et al. 2000). These studies support the view of Davenport (2009) that pre-flowering water stress in low-latitude grown mango trees can be important to prevent shoot initiation and therefore delay flushing. The reports of negative yield responses to high irrigation rates (da Silva et al. 2009) appear to be related to post-flowering irrigation rates rather than to pre-flowering applications. However, this requires further clarification.

Interactions between irrigation and other management practices that affect fruit carrying capacity of mango trees also appear important for fruit number. Major effects on vegetative growth were identified in paclobutrazol-treated trees that did not receive pre-flowering irrigation (Gonzalez et al. 2004) and mango tree root production was limited by the use of morphactin (Blaikie et al. 2004). Despite the widespread use of paclobutrazol and other flowering treatments in the NT and other parts of Australia, there has been only one study that evaluated the irrigation practices that are needed to support the use of paclobutrazol (Diczbalis & Wicks 1996). That study identified that paclobutrazol-treated trees required pre-flowering irrigation at 13 to 25 mm/week. Studies are required at a range of sites and tree ages to identify irrigation practices that support high fruit numbers per tree following the use of paclobutrazol or other flowering treatments.

Providing adequate irrigation has clear benefits for mango fruit number, especially during fruit-set (Bhambid et al. 1988; Chandel & Singh 1992). However, it is unclear how and when high irrigation rates will reduce fruit numbers (Kumar et al. 2008) or total yields (da Silva et al. 2009). Hence, work is required to determine:

1. What irrigation practices are required to support optimal fruit numbers following the use of paclobutrazol or other flowering treatments.

2. The relationship between increased irrigation volume during flowering and irrigation post-flowering, on final fruit number; in particular, it is important to identify irrigation practices that maximise fruit number.

Fruit quality

A range of both positive and negative effects on fruit quality have been reported. Differences between studies may be linked to differences in irrigation treatments (droughting for set periods, pre-harvest cessation of irrigation, or reduced season-long volumes) and whether the studies were carried out in an environment where effective rainfall occurred during fruit development or it did not.

In an environment where effective rainfall occurs during cropping and moisture stress is minimal, ceasing irrigation at early fruit development can provide some benefits to fruit quality. For example, in Kenya, ceasing irrigation ~40 days after flowering gave firmer fruit with higher anthocyanin levels and a longer shelf-life than fruit from trees irrigated throughout the year (Madigu et al. 2009). In another study with mild water stress, fructose levels were higher in the fruit where irrigation ceased 30 days after flowering but these trees also received 170 mm of rain prior to harvest (Lechaudel et al. 2005).

In contrast, the droughting of trees during early fruit development that results in water stress as indicated by reduced stomatal conductance can result in reduced fruit quality (Simmons et al. 1995). In trees with no irrigation from flowering to 12 weeks post-flowering before the resumption of irrigation, fruit at harvest was greener and smaller than fruit from fully irrigated trees (Simmons et al. 1998).

In dry environments, the early cessation of irrigation prior to harvest had both positive and negative effects. Cessation at 7.5 weeks prior to harvest increased fruit blush intensity, total soluble solids and DM levels but reduced the shelf-life of fruit ripened at 22 °C and resulted in more green fruit than in trees irrigated to harvest (Simmons et al. 1995; Simmons et al. 1998). However, the cessation of irrigation from either 7.5 or four weeks prior to harvest decreased the level of fruit lenticel spotting (Simmons et al. 1995). The quality of cold-stored fruit (10 °C) was negatively affected by the cessation of irrigation at 7.5 weeks prior to harvest, with the proportion of internal and external chilling injury five to 10 times that of fruit irrigated to harvest (Simmons et al. 1998). In the NT, it was observed that fruit forced to reach a dry matter of 14% by early cessation of irrigation, tended to be of a lower quality (Diczbalis 1994b).

Few studies have investigated the effects of reduced season-long irrigation on fruit quality, particularly in dry environments. A study in Thailand where high levels of rainfall occurred during cropping in some seasons, reported that post-harvest fruit quality was not adversely affected by reductions in irrigation volume of up to 50% of ET_P over the season (Spreer et al. 2007) (Appendix 8). The peel colour (degrees hue angle) seven days after harvest in fruit from trees irrigated at 50% of ET_P was greater than in fruit from fully-irrigated trees, while pre and post-harvest mesocarp colour, fruit firmness, glucose, fructose, maltose and sucrose levels did not differ in fruit from fully- irrigated trees (Spreer et al. 2007). In contrast, in the environment of the NT where little or no effective rainfall occurs during fruit development and growth, irrigation at 40% of pan evaporation resulted in greener fruit at the soft-ripe stage than fruit from trees irrigated at 100% of pan evaporation (Diczbalis et al. 1995a).

The effect of reduced season-long irrigation volumes (as opposed to droughting or the early cessation of irrigation) on physiological disorders remains an area that has not been well addressed. In the NT, high levels of fruit lenticel spotting and poor post-harvest storage capability have been associated in industry surveys with apparent over-irrigation during fruit fill (Baker 1992). It is unclear what level of irrigation may result in lenticel spotting above the minimum acceptable level.

In a number of fruit crops, some benefits have been reported from reduced irrigation. For example, deficit irrigation practices in grapevines were associated with an increase in vitamin C, phenol and anthocyanin contents in the fruit (Santos et al. 2005; Du et al. 2008). In some cases, such benefits were identified as being due to indirect effects from a reduced canopy and increased exposure of the fruit to radiation (Santos et al. 2005). In mangoes, an improved knowledge of the causal mechanisms involved in the effects of irrigation on both positive and negative aspects of fruit quality would assist in identifying which management practices can be used to improve fruit quality.

The work of Diczbalis et. al (1995a) identified that in the dry cropping season environment of the NT, large season-long irrigation reductions (e.g. 40% of Epan verses 100% of Epan) can reduce fruit quality aspects such as fruit colour. It is unclear if smaller reductions in season-long irrigation volumes would cause the same effects. Studies overseas have indicated that water requirements of mango trees increase following fruit-set (de Azevedo et al. 2003). The effects of reduced early season volume followed by higher volumes during fruit fill on mango fruit quality have not been addressed in earlier studies. The identification of any benefits from reduced season-long irrigation practices on fruit quality would be important as an added impetus for the uptake of WUE practices by mango growers. Work is required to determine:

1. The impacts of reduced season-long irrigation on physiological disorders, such as lenticel spotting.

2. Whether the benefits of reduced season-long irrigation on fruit quality that are reported in a number of other fruit crops are relevant to mango fruit quality.

3. The effects of reduced season-long irrigation and reduced early season irrigation on fruit quality in seasonally-dry environments, in particular with regard to post-harvest storage and quality.

Long term and vegetative effects of irrigation

This review has focused on within-season yield responses to irrigation practices without considering season-to-season effects. Cull (1987) stressed that it is useful to adopt a whole-life cycle approach to understand the effects of management on mango yield and vegetative responses. As mangoes are a perennial crop, the carry-over effects of management practices from one season to another are important in the longer term. This section identifies a number of areas where the longer-term effects of irrigation management in mango production may affect vegetative growth and associated fruit yield.

Deficit irrigation practices have reduced vegetative growth in a number of tree crops (Romero et al. 2004; Cui et al. 2009; Iniesta et al. 2009). These effects may be viewed positively in crops such as pears as they reduced pruning but not yields (Cui et al. 2009), or negatively in post-harvest deficit (50% of ET_P) applications in an arid environment that led to smaller almond trees and reduced yields over four years (Romero et al. 2004).

Vigour management in mango trees is an ongoing task, especially for precocious varieties, such as Kensington Pride (Crane et al. 2009; Knight et al. 2009). Work on other crops suggests that vigour management in mango trees may be assisted by irrigation management; however, the effect on yield needs to be closely examined in conjunction with vegetative responses.

A number of studies demonstrated that vegetative growth in mango trees is affected by the irrigation regime. However, there are few, if any, long-term studies (five or more seasons). A pre-flowering irrigation study in the NT carried out over three seasons identified that not providing pre-flowering irrigation to trees receiving flowering-promoting treatments resulted in smaller diameter trunks and a reduced LAI compared with trees that received irrigation pre-flowering (Gonzalez et al. 2004). Fruit yield tended to be lower by ~3 kg/tree in non-pre-flowering irrigated trees (P = 0.067) in the final year (Gonzalez et al. 2004). Young four-year-old mango trees had negative vegetative responses to irrigation regimes, where deficit irrigation caused reduced trunk diameters but had no effect on yield in a one-year study in South Africa (Pavel & de Villiers 2004). Reduced season-long deficit irrigation practices have been evaluated in the NT for single seasons (Diczbalis 1994b; Diczbalis et al. 1995a). It would be important to evaluate the longer-term impacts of multiple seasons of reduced irrigation since potential effects are unknown and, as in other species, could be large (Romero et al. 2004).

Water use by mango at the tree level has been quantified in the NT through the use of sapflow methods (Lu 2002, 2005). However, more information is required that separates water need from water use. It is also unclear if the level of water use identified above includes 'luxury' consumption. Luxury consumption is defined here as water used above what the tree requires to produce the crop and above what the tree requires to support growth and reserves for the following season's crop.

Post-harvest irrigation is used in a number of orchards in the NT from final harvest to the start of the wet (Diczbalis et al. 1995b). Both the mango harvest date (Appendix 7) and the length of the dry season differ each season (Mollah & Cook 1996; Cook & Heerdegen 2001) which may necessitate post-harvest irrigation in some seasons but not in others. The timing of vegetative flushes following harvest had been related to the earliness of the following flowering through a tissue age effect in conjunction with other factors (Davenport 2007). Improved post-harvest irrigation management in some tree crops has assisted in promoting early flowering and harvests (Cuevas et al. 2009). As mango harvest dates in some regions of the NT and during some seasons can occur one to two months prior to the start of the wet season (Appendix 7), it is possible to evaluate the effects of post-harvest irrigation to assist with early season mango production. However, up to now the utility of post-harvest irrigation to promote early vegetative flushing has not been investigated.

Although root drying is reported to benefit WUE and yield levels in some crops (Dry & Loveys 1998; Stoll et al. 2000; Costa et al. 2007), Davenport (2007) has contended that irrigation practices in mango production that allow parts of the root system to dry out produce other problems. Dry roots lead to the accumulation of cytokinins in dry root tips, which leads to a vegetative flush following the first rains, when the complete root system gets wet. Davenport (2007) identifies irrigation systems, such as drippers, as problematic for the management of vegetative flushes, especially where the promotion of an early vegetative flush prior to the first rains is desired. The importance of irrigation delivery system to the management of vegetative flushing appears not to have been investigated in Australia.

The wet season in the NT is made up of both wet and dry periods. For example, on a fortnightly basis from December to February, the variability in total rainfall in Darwin ranged from 59% to 77% (% coefficient of variation) over 103 seasons (Mollah & Cook 1996). Part of the water allocation (8.6 ML/ha) for mango growers in the Tindall aquifer included water for irrigation in drier than usual wet seasons (Anon 2009b). Studies in the NT and overseas have identified that water use by mango trees is at its highest during the wet season (Lu 2002; Teixeira et al. 2008). Although water has been allocated for mango production, it is unclear how important water deficits are during the wet in affecting vegetative parameters and associated yields. Information is required on the effects of dry periods during the wet season and the supplementary use of irrigation during that period. Current mango irrigation recommendations have been developed for dry-season fruit production (Appendix 1). The applicability of these recommendations to the wet season is unknown, especially as dry breaks in the wet will typically occur following periods of total soil saturation with water also available at depth.

Work in a number of areas is required to determine:

1. What the long term (five or more seasons) impacts are of reduced season-long irrigation on mango vegetative growth and associated yield in an environment with no effective rainfall during the irrigation season.

2. The effects on orchard operating costs e.g. of pruning following reduced season-long irrigation through to long-term effects on vegetative growth.

3. If 'luxury' tree water supply occurs and at what irrigation level.

4. The effects of post-harvest irrigation, including delivery method (drip vs. sprinkler) on the earliness of vegetative flushing, flowering and early fruit production.

5. The needs and effects of irrigation during dry breaks in the wet season.

Seasonal variation in requirements

In order for irrigation to be efficient, there is a need to supply water to mango trees when it is needed and at the required volume.

An NT study found that water use by mango trees varied during the season. For example, at the initiation of irrigation following flowering, water use was low in commercial orchards in the month following flowering (mid August to mid September) (Diczbalis & Bowman 1991, 1992). Sapflow values in Kensington Pride trees also indicated water use was lower during this period than during fruit fill in the NT (Gonzalez et al. 2004). This finding was supported by overseas studies (de Azevedo et al. 2003; da Silva et al. 2007; Teixeira et al. 2008). For example, water use was highest from 80 to 130 days after flowering from mid fruit growth to mid fruit maturation (de Azevedo et al. 2003). Lu's (2005) dendrometer piloted schedule results also indicated non-consistent requirements as less water was applied to the dendrometer treatment, but proportionally more of this water was used than in other treatments, thus indicating differing requirements over time. For growers applying the same irrigation volume throughout the season, one of the main opportunities to better match the delivery volume to the trees' requirements may include reducing early season irrigation following a clear quantification of requirements.

Kensington Pride is the predominant mango variety grown in the NT and in Australia. It has a reduced stomatal conductance with increasing leaf to air vapour pressure deficit (VPD) levels (Schaffer et al. 2009). VPD levels in the NT peak near the end of the dry season (Duff et al. 1997). A detailed study of Kensington Pride, Irwin and Tommy Atkins in Kununurra demonstrated that Kensington Pride had approximately half the level of net photosynthesis, often less than half the level of stomatal conductance and transpiration during the dry season during high VPD (range ~15 to 31 millibars) (Johnson 1998). In the wet season, these parameters differed only moderately during a VPD range of ~8 to 22 millibars, except at one time when VPD rose to 25.5 millibars at midday and was associated with a decline in net photosynthesis, stomatal conductance and transpiration in Kensington Pride only (Johnson 1998). These results indicate that water use will be reduced during high VPD conditions due to reduced transpiration. VPD can be predicted from relative humidity and air temperature (Passos et al. 2009). It would be useful to establish what the seasonal pattern is for VPD in mango growing areas and how seasonal VPD affects the level of water use in Kensington Pride trees.

In general, there is a need for a better understanding of the effects of environmental factors on seasonal transpiration levels on commercial orchards, especially in Kensington Pride, in addition to other popular varieties, such as Calypso (B73) and Honey Gold.

Understanding the potential effects of climate change on seasonal water requirements will also be important given that the number of days in which the temperature is predicted to exceed 35 °C in Darwin. Current forecast based on the period of 1971 to 2000 predict a rise from 11 to 44 days by the year 2030 for mid level greenhouse gas emissions and up to 89 days for low level emissions by the 2070 (Hennessy et al. 2010).

Work in a number of areas is required to determine:

- The seasonal water requirements of common mango varieties in the NT environment.
- Periods of high VPD or other environmental factors that affect water use in NT orchards.

Quantifying water requirements with crop factors or coefficients

The current recommendations are based on a crop factor of 0.7 linked to mean pan evaporation values (Appendix 1). This crop factor value was based principally on two data sources. First, data collected from on-farm irrigation monitoring work over a number of seasons, which showed a rapid increase in soil tension in the 20 to 40 cm depth range when moisture inputs from either rain and/or irrigation fell below 70% of evaporation rates (Y. Diczbalis, unpublished data) and second, DM and size response to irrigation inputs based on evaporation replacement rates from 40% to 100%. Fruit continued to increase in size with increasing evaporation replacement rates up to 100%. But fruit DM at harvest declined with increasing irrigation (Diczbalis 1994b). An evaporation replacement of 70% was selected as a compromise, which allowed sufficient fruit size and DM development at harvest whilst still allowing mature green fruit to ripen in seven to 10 days after harvest.

The crop factor of 0.7 may be useful as a figure at which the crop is relieved from moisture stress across a wide range of conditions. However, it may risk adverse in some situations as studies at particular sites have indicated that lower values may suit some sites or crops. For example, monitoring gave a crop factor 0.47 during September at one site in the NT (Diczbalis & Bowman 1991, 1992). The irrigation of large mature trees in Israel was also based on comparably low crop factors of 0.3 to 0.4 (% of pan evaporation) (Crane et al. 1997). Sapflow measurements in trees in the NT scheduled at 80% of pan evaporation indicated that only 31% of it was used by the tree, with other scheduling methods providing greater irrigation efficiencies of 38% and 77% (Lu 2005). These results suggest that lower crop factors in mango trees may be used in some circumstances. Work has also indicated that in areas with high levels of pan evaporation, potential evapotranspiration is usually lower than pan evaporation (Chiew et al. 2002). The use of pan coefficients are also very important when using pan evaporation to guide scheduling (Allen et al. 1998), especially under dry season conditions when pan levels do not relate well to potential evapotranspiration as demonstrated by data from Darwin (Chiew & McMahon 1992).

The use of potential evapotranspiration may be more accurate than pan evaporation in a wet-dry environment, during periods of high pan evaporation readings (Chiew et al. 2002; Kirono et al. 2009). In a Darwin study, potential evapotranspiration values from March to late October did not exceed 4 mm a day and ranged from 2 to 4 mm (Lu & Chacko 2000). During the same period, average monthly pan evaporation levels ranged from almost 6 to 8 mm daily. Values would have been higher during some periods. It would be useful to compare the potential evaporative demand based on pan evaporation and evapotranspiration data with actual mango tree water use. In addition, the levels of crop evapotranspiration (as opposed to potential evapotranspiration) have not been determined in mango orchards on a seasonal basis in the NT or in other parts of Australia. On a commercial mango orchard in Brazil, crop evapotranspiration ranged from 3.13 to 4.63 mm/day (Teixeira et al. 2008).

Results of studies overseas have also indicated that crop coefficients used for mango trees of 0.75 (da Silva et al. 2009) and 0.8 (Spreer et al. 2007; Spreer et al. 2009) were too high, as lower application rates provided higher or similar yields. Crop coefficients are based on evapotranspiration data. Due to the absence of crop evapotranspiration data in mango trees in the NT or in other parts of Australia, it is not possible to determine if projected water applications based on these values would provide more or less than that based on the recommended crop factor and pan evaporation data.

It is unclear if the crop factors or coefficients are simply too high or are accurate for fully transpiring trees, but environmental factors, such as vapour pressure deficit (Johnson 1998; Schaffer et al. 2009), cause a decline in transpiration and hence water use. However, it appears that the use of a single factor and coefficient throughout the irrigation season is inappropriate since lower values are needed from flowering to fruit-set compared with the fruit fill period (de Azevedo et al. 2003). Reduced inputs early in the season would result in 20% to 30% savings in irrigation water during the first half of the season compared with current recommendations.

Work is required to:

1. Identify accurate crop factors or coefficients for common mango varieties in the NT, including for pre-flowering and post-harvest periods when irrigation may be used.

2. Identify if potential crop water use is more accurately determined through pan evaporation or potential evapotranspiration methods.

3. Identify ETcrop in mango trees.

WUE irrigation strategies for mango trees

In the past 20 years, a number of strategies have been developed to improve the efficiency of water use in agriculture (Anon 2002b; Oster & Wichelns 2003; Costa et al. 2007; Geerts & Raes 2009). One strategy is 'deficit' irrigation. This is described as irrigation maintenance at rates below that expected to meet water required for evapotranspiration (Costa et al. 2007; Geerts & Raes 2009). The deficit irrigation approach has two general methods:

a. Where constant deficits are applied across the whole season, or on a supplemental basis if irrigation occurs for a short period only. This method was used in mango studies, e.g. replacing 70%, 80% or 90% ETP across the irrigation season for crop coefficients of 0.75 or 0.8 (da Silva et al. 2009; Spreer et al. 2009).
b. Where the volume or scheduled volume differs according to critical phenology. This is sometimes described as regulated deficit irrigation (RDI) (Costa et al. 2007) or as 'drought stress differentiated by phenological stage' (Geerts & Raes 2009). An example is where different replacement volumes of crop factors are used for different phenological intervals. For example, in almonds, RDI was used at 50% of ETP during the kernel-filling stage but 100% ETP throughout the remaining periods (Egea et al. 2009). Alternatively, different factors or coefficients can be used for different periods.

The latter method, although identified as appropriate for mango trees (de Azevedo et al. 2003), has not been investigated. However, that method requires detailed knowledge of the water requirements of each phenological period (Goodwin & Boland 2002b; Costa et al. 2007). In comparison, the first method will be easier to operate and requires less information, but is not tailored to the crop's changing requirements through time.

Another application method is that of partial root zone drying (PRD) which splits applications from one side to the other side of the tree, with alternate drying of root zones being the underlying principle. The volumes of application or scheduling are usually applied on a deficit-irrigation basis. This method is receiving widespread attention in high value horticultural crops (Costa et al. 2007). However, a recent meta-analysis comparing RDI and PRD from a large number of studies of horticultural crops indicated that PRD resulted in only a small increases in yield (average ~5%), compared with RDI (Sadras 2009). Also, while RDI uses existing irrigation systems, PRD requires a specialised configuration of irrigation lines. The small difference in yield between RDI and PRD irrigation treatments may not support the additional investment required for PRD (Sadras 2009). A comparison of RDI and PRD in mango production demonstrated no clear advantage (Spreer et al. 2007).

There is a need to evaluate RDI strategies once seasonal water use or crop coefficients are available.

Rootstocks and root distribution

Substantial differences in the ecophysiology and associated water relations between varieties of mango scions have been reported in Australia (Johnson 1998; Lu 2002). However, rootstocks are another important factor. A number of mango rootstocks have been identified as providing improved yields or leading to less vigorous vegetative growth in Kensington Pride in the NT (Smith et al. 2003; Smith et al. 2008). In a number of other tree crops, such as apples and peaches, rootstocks imparting low vigour or dwarfing characteristics were associated with reductions in hydraulic conductivity or rapidity of water transport in the xylem (Cohen & Naor 2002; Basile et al. 2003; Fassio et al. 2009). The identification of mango rootstocks that either contribute to reduced vigour and an improved harvest index, or have more water efficient root systems, would contribute to improve WUE in mango production in the NT.

There is limited available information on the active fine root zone in mango trees. Results from trees that were severely droughted indicated some uptake from below the 800 mm profile but measurement of root activity in irrigated trees was higher at 150 mm and 300 mm, than at 600 mm or 900 mm, depending on the time of sampling (Bojappa & Singh 1974; Johnson 1998). There is little information on the root distribution in mango trees in different soil types for different varieties and rootstocks. Current recommendations are that the saturation of the soil below 800 mm indicates over-watering (Appendix 1). Determining the active fine root zone would assist in identifying suitable wetting depths to improve WUE.

Work is required to:

1. Evaluate mango rootstocks for WUE attributes.
2. Determine vertical fine root distribution or effective rooting depth for common mango varieties.

NON-TREE AND SITE FACTORS TO IMPROVE WUE

There are a number of factors not directly related to the mango tree and associated with site management practices or the effects of these practices. Information on quantifying losses from non-tree factors includes losses from: deep drainage, evaporation, method of irrigation delivery such as sprinkler or dripper; and effects of soil type. Information on these factors would assist in developing a site based account of efficiency, in turn this information could be used to support efficient irrigation practices and scheduling. Information on current practices across the industry is also required. This section addresses these areas.

Soil water information

It is often pointed out that soil type does not affect how much water a plant may require. While technically correct, under controlled conditions, soil type has a major effect on the availability of water to a plant (Stanhill & Vaadia 1974). Thus soil type affects water availability, which affects plant water use.

A number of common soil types used in horticulture in the NT, such as sandy red Kandasols (Blains) have a high sand content, low clay and low organic matter and hence low water-holding capacities (Slatyer 1954; Day 1977). It is unclear how well growers understand water-holding capacity and infiltration rates of their soil types and if they use suitable irrigation practices for particular soil types (Anon 2009a). Large differences in deficit-irrigation effects were observed on fruit size between a sandy loam and sandy site in one trial (Diczbalis et al. 1993). Recommendations for soil water levels differ for mango orchards between soil types in Brazil, with coarse textured (sandy) soils maintained at -15 to -25 kPa and fine (silts) textured soils at

-30 to -60 kPa (Coehlo & Borges 2004). The physical attributes of soils on grower properties in the NT need to be examined and implications identified for irrigation frequency and volume. The use of irrigation practices tailored to particular soil types will be required to optimise WUE. Variable soil types on a single property can pose difficulties to efficient water use. In some areas, such as Loxton South Australia, it is recommended that during the planning of new orchards, detailed soil mapping of sites be undertaken to lay out irrigation blocks on a common soil type for irrigation efficiency (Diczbalis 1990).

There are two main areas where practices to reduce water loss from the soil may occur. The first is losses from the soil surface and the second is from deep drainage.

Water losses at the soil surface

In a commercial mango orchard in Brazil, up to 20% of irrigation water was lost through soil evaporation (Teixeira et al. 2008). There is little information on the level of evaporative losses on NT orchards during the dry season irrigation period. Monitoring of a wet season millet crop in Katherine showed a maximum evaporation of about 10% (range 7-10%) from the soil as a proportion of total evaporation (Begg et al. 1964).

Mulches can be used to reduce evaporative losses from the soil surface. A number of studies have demonstrated the successful use of organic or non-organic mulches in mango production (Gregoriou & Kumar 1984; Kumar et al. 2008). Higher yields and increased WUE have been reported in mulched trees (Singh et al. 2003). Mulches or grass sods also reduced mango canopy temperatures by more than 8 °C in India (Burondkar et al. 1994). This effect may be useful during temperature-sensitive phenological events. Although mulches can be effective at reducing evaporation from the soil surface, they may require specialised management. NT mango growers have expressed interest in the use of prostrate ground covers that self mulch (Anon 2009a). These issues require evaluation before recommendations can be made for the NT.

Irrigation delivery systems, such as drippers, are more water-efficient than sprinklers primarily due reduced evaporative losses at the soil surface or to direct evaporation of water in the air prior to soil contact. Therefore, the delivery method of irrigation is an important component of reduced irrigation losses. Mango irrigation systems in the NT (which largely use sprinklers) have an estimated average efficiency of 85% (pers. comm. M. Bennett). Improvements in delivery efficiencies can be made by limiting off-target application, losses to wind and evaporation, and run-off. Dripper delivery systems provided improved WUE for new mango plantings in the NT (Wicks et al. 1999a) and can have efficiencies of up to 90% (Solomon 1993). However, drippers for mature trees are unpopular because blockages and malfunctions are not as visible as in sprinklers (pers. comm. M. Bennett). Subsurface drippers further reduce the potential for evaporative losses at the surface. Subsurface drippers in other tree crops have been successful in improving WUE and were associated with a deeper and denser fine root system (Romero et al. 2004).

Water losses through drainage

Information on deep drainage losses is essential for identifying over-watering. Some information is available on deep drainage losses in cotton in the NT (Martin et al. 2006) but not in mango crops. Although soil moisture and tension were identified in a commercial orchard as sufficient for drainage to occur in October (Diczbalis & Bowman 1992), early season results did not indicate any probable deep drainage. Soil type will be an important factor affecting the potential for deep drainage losses. In a mango orchard in Brazil, deep drainage losses as high as 50 mm per month were reported on some occasions (Teixeira et al. 2008). There is insufficient information to assess if deep drainage losses are occurring under current practices in NT mango orchards. As deep drainage occurs out of sight of the grower, quantifying its level is important for improving WUE.

Soil water or plant monitoring

Irrigation of high-value crops, such as cotton, grapes and fruit trees in Australia is based on the use of objective irrigation scheduling tools (such as crop evaporation data, soil moisture sensors or consultant services) more than in other crops, such as pasture (Montagu & Stirzaker 2008). However, the use of tools to support scheduling decisions even in high-value crops is still quite low in Australia, at 27% (Montagu & Stirzaker 2008). A survey of mango growers concluded that although moisture monitoring equipment had helped growers to make decisions about irrigation timing, presumably by providing improved information on soil-water or plant-water status, such as when to irrigate following dry-point identification, there were still information gaps regarding the frequency and volume of application (Anon 2007).

A wide range of soil and plant water status equipment is commercially available (Jones 2004, 2007). Katherine irrigators reported using a range of technologies, such as Diviner and Enviroscan (Straton et al. 2006b) but the prevalence and use of these or other tools across the NT mango industry is unknown. A dendrometer method was identified as a very efficient means of regulating irrigation in mango orchards in the NT (Lu 2005). Initiatives, such as the dendrometer method that identify superior soil or plant monitoring systems, need to be supported with further research and development to make them available to mango growers.

Irrigation scheduling

Irrigation scheduling includes a number of components, such as the phase of the crop to initiate or cease irrigation, and frequency and volume of irrigation. The optimisation of scheduling will also require information from the plant-based research identified earlier in the Mango Ecophysiology Section.

Information is available on when to initiate irrigation during the fruit production phase. It is recommended to start irrigation at 60% flowering (Appendix 1). Studies in the NT indicate that mango trees receiving flowering treatments require irrigation prior to flowering (Diczbalis & Wicks 1997; Gonzalez et al. 2004). The effects of early (pre-harvest) cessation have been well studied in the NT (Diczbalis et al. 1993; Diczbalis et al. 1995a). The initiation and cessation timing during the post-harvest period requires evaluation. Following the decision to irrigate at a given crop phase, the scheduling principally involves two central aspects, frequency and volume.

Irrigation frequency recommended for sandy soils in the NT is at two to three times a week for areas that do not cause deep drainage. Soil moisture tension at 20 and 40 cm, as measured by a tensiometer, should be kept under 30 to 40 kPa, depending on soil type. Tension at 80 to 100 cm should be between 40 and 60 kPa (Appendix 1). Observations also indicate that irrigation for 4 hours every second day (14 hours/week, at the rate of at 72.5 L/hr, providing 1015 L/tree/week) keeps the water level sufficiently high in the top 60 cm of the soil (Diczbalis & Bowman 1991). Further NT guidelines for irrigation trigger points using tensiometers recommend irrigation at tensions above 25 to 35 kPa on sandy soils, 35 to 50 kPa on loam soils and 50 to 60 kPa on clay soils (Owens et al. 2003). The initiation of irrigation should be based on the results of monitoring. Trigger points for irrigation will differ depending on the monitoring system used (Jones 2004, 2007). Since there is no clear information on suitable trigger points to initiate irrigation in mango orchards in the NT, specific protocols need to be developed.

There are no prescriptions for the volume of application because that depends on canopy area, irrigation efficiency, environmental conditions and tree requirements based on phenology (Appendix 1). Soil type will be an additional factor. The volume to apply is also affected by the frequency of irrigation. For the same volume of water, small but more regular applications give greater WUE than large volumes applied less regularly. There is a need to establish a balance point between increased operating costs due to more frequent applications and improved WUE.

Recommended methods have been developed in South Australia for calculating the frequency and rate of irrigation in deficit-irrigation regimes for fruit trees based on the theoretical volume that the root zone can hold and the average daily water use for particular soil types (Goodwin & Boland 2002a). As this method is based on the water-holding capacity of a soil, it can be adapted to local soil types in the NT. An evaluation of this method for calculating irrigation frequency on NT orchards would assist in providing improved irrigation management to mango producers.

Current practices

NT horticultural producers, including mango growers, identified the understanding of the water requirements of their crops as their biggest knowledge gap (Anon 2009a). Secondary requirements included information on cost-effectiveness of different systems and moisture-holding capacity of their soils in relation to irrigation scheduling (Anon 2009a). A survey of management practices of mango growers in Australia across all growing areas including the NT representing 300 000 trees, reported industry uncertainty regarding appropriate rates of irrigation in mango trees to achieve optimum production and fruit quality (Anon 2007).

There is little information on common irrigation practices in mango orchards in the NT and the range of practices. In 1995 some growers were estimated to provide up to double the weekly volume of water needed (Diczbalis et al. 1995c). It is unclear if this observation is relevant to contemporary practice. Information is needed on irrigation practices in the NT in order to identify areas for improvement. Fundamental to this knowledge gap would be the identification of periods of over or under supply of water and subsequent means of correction.

Rating WUE performance

To improve WUE in NT mango orchards, there is a need for a method to compare and rate efficiencies. For Kensington Pride, which is known for its seasonal variability in yield (Beal & Newman 1986; Bally et al. 2002), multiple season yields and water consumption figures will be required as results from single low yielding seasons will not be informative (Table 13). Currently there is a lack of any WUE information on commercial orchards. The use of field trial data provides an indication of the probable range (Table 13), but does not include consumption figures for post-harvest irrigation. WUE from a number of trials provides values of more than 30 kg/m^3 which could be obtained from moderate yields (more than 50 kg/tree) and application volumes of less than 20 000 L/tree. These figures, when compared with another low yielding variety in Thailand, indicated NT producers could achieve adequate efficiencies when crop yields were average or above average (Appendix 8).

A study in Queensland reported that some growers can achieve high WUE values by irrigating 1.5 to 3 ML/ha for yields of 9 to 11 t/ha. However, average values were 5.5 ML/ha for 7.3 t/ha (Anon 2002a). An earlier survey in Queensland in 1999 reported an average use across a survey group of 5.5 ML/ha for yields of 4.9 t/ha (Anon 1999). Also in Queensland, a best practice group of producers achieved an average of 11.1 t/ha from 2.4 ML/ha of irrigation. These studies did not provide rainfall levels during fruit development, which makes comparison between the wetter Queensland conditions and the drier NT conditions difficult (Beal & Newman 1986). However, this supports the need for best practice groups in the NT to improve WUE in mango production.

WUE is currently linked to gross yield (kg/tree or ha). It may be useful to also link water use to fruit quality, such as the proportion of class 1 fruit produced. Information is needed to identify best practice WUE and to assess WUE in mango orchards in the NT.

Information is a needed to improve on-farm WUE practices, such as:

1. Information on soil properties in terms of water-holding capacities and infiltration rates to improve irrigation practices.

2. Information on levels of soil surface evaporative losses and the effectiveness of methods to reduce them, including the use of mulches and irrigation delivery systems.

3. Information on deep drainage losses.

4. Guidelines to support a range of soil and plant monitoring systems and further develop them.

5. Information to develop optimal irrigation schedules such as:

    a. Timing - there is no information on post-harvest scheduling practices.
    b. Frequency – although some information is available on tensiometers, there is little information on other appropriate soil water measurement systems for non-tension monitoring on common soil types.
    c. Volume and frequency - although methods based on soil volume to be wetted have been developed for fruit tree irrigation in other parts on Australia, there is little information on their adaptation for WUE in mango orchards in the NT.

6. A description of the range of current irrigation practices and schedules used by growers in the NT to identify where improvements can be made, including linking the effects of current practices with yield and quality, yield in relation to water use and identifying a benchmark for future WUE performance comparisons.

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APPENDIX 1

Agnote

No: D14

June 2006

Mango Irrigation Management Guidelines

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Introduction

Irrigation management is crucial to the production of quality fruit. Water inputs must be geared to tree water requirements, soil factors and fruit physiological requirements.

New Planting

In a new planting, trees must be irrigated throughout the year, including dry periods which occur during the wet season, to enable rapid establishment of the tree. Water inputs should be appropriate to tree size. In general up to 100 L/tree/week should be sufficient for the first two years. The radius of the sprinkler should be appropriate to tree size. Many growers find that a sprinkler with a distributor plate (radius of 1.0 to 1.5 m) is adequate for up to three years. In subsequent years sprinkler radius should be less than 3 m to ensure that the water is delivered to the root zone under the canopy edge which also helps to reduce weed growth around trees. After the second wet season trees are generally only irrigated during the flowering and fruit development period. (July to November)

The soil type determines how early continuous irrigation can cease. Trees grown on light sandy and gravelly soils may require continuous irrigation for a longer period to allow them to develop an appropriate size canopy.

Fruiting Trees

In fruiting orchards there are three phases during the annual growing cycle where distinct irrigation management options need to be exercised.

- **Phase One**
  Pre-flowering, from the end of the wet season to the commencement of flowering (April to June/July).

- **Phase Two**
  Flowering and fruiting, from visible panicle bud differentiation to harvest (July to November).

- **Phase Three**
  Post harvest to the end of the wet season (November to April).

Phase one

In mature orchards (established fruiting trees) water is normally withheld from the end of the wet season until flowering. This period of low soil moisture is believed to encourage earlier and more synchronous flowering. Experimental evidence is still inconclusive but it is thought that cool weather (several weeks with night temperatures less than 15°C) is the main flowering trigger. However, irrigation withdrawal is thought to enhance the flowering trigger, particularly in a year where there is an inconsistent run of cool nights.

Phase Two

Irrigation is highly recommended from flowering until late fruit maturity. Some growers prefer to start irrigating after 50% of the tree is in flower and at least 50% of the flowers are open. Other growers will start irrigating from the commencement of visible flower panicle development in an attempt to speed up the flowering and fruit setting process. The present DPIFM recommendation is to start irrigating when at least 60% of the flower buds are visible.

The amount of irrigation is dependent on tree size (canopy cover), evaporation rates and evaporation replacement rate. Irrigation frequency is dependent on soil type (water holding capacity) and effective root depth.

The present irrigation input recommendations are based on a replacement rate (crop factor) of 0.70. Irrigation rates (Appendix 1) per tree depend on the size of the tree. Planting density and pattern interacts with tree size. Maximum percentage canopy cover in the orchard should be between 60% and 70%. This can be achieved by a few large trees (e.g. 100 trees/ha 10 x 10 m) or many smaller trees (e.g. 200 trees/ha 10 x 5.0 m).

Many growers choose to water for 24 or 36 hours at the start of the irrigating season. This may not be necessary particularly if using low radius (2.0-3.0 m) sprinklers because tree water requirement is lower during the first month of flower and fruit development. The use of a hand auger to establish watering depth is recommended, particularly during the first few weeks after irrigation commences. The wetted zone should be at least 40% of the under tree canopy area and good soil moisture should occur down to 60-80 cm. Saturated soil beyond 80 cm suggests that trees are being over watered.

Phase Three

Irrigation normally ceases a few weeks prior to harvest and is not recommenced until flowering in the following year. In years where the wet season begins late (late January, early February) the new vegetative flush may be delayed. This may influence the following flowering date with the most likely consequence being a later flowering. In situations where trees are grown on light soils and the build-up rains and wet season are late, trees should be irrigated to promote an early flush of growth. This should occur after pruning and fertiliser operations have taken place.

Soil Moisture Monitoring

Monitoring of soil moisture status using tensiometers, neutron moisture probes or the capacitance based Environscan is an extremely useful management technique, particularly in larger orchards. Tensiometers are the simplest and least costly instruments to install and use. Tensiometers should be installed in groups of two or three with the shallower tensiometers at 20 and 40 cm and the deepest at 80 to 100 cm. Tensions in the two shallower depths should be kept under 30 to 40 kPa depending on soil type whereas tension at 80 to 100 cm should be between 40 and 60 kPa. See Agnote D19 “Tensiometers” for more details. The Neutron Moisture Probe and Enviroscan can give additional information such as watering depths and depth of water uptake which allows for further refinement of irrigation schedules. However, they require good computer and management skills to interpret. Needless to say these instruments should be considered by owner/managers of larger orchards. In all circumstances, regardless of water monitoring techniques, growers should record watering times and duration throughout the growing season.

Irrigation Frequency

In simple terms the more sandy and gravelly the soil, the more frequent irrigations should be. Two to three times per week will be appropriate for most sandy sites. Long irrigations on a sandy soil result in water draining beyond the depth of the effective root zone which is a waste of water and leaches away nutrients. The use of a hand auger to determine irrigation depth can quickly alert you to potential deep watering problems. Moisture monitoring will allow an appropriate irrigation schedule to be established.

Water Requirements and Fruit Dry Matter Manipulation

Some growers encourage the earlier development of 14% fruit dry matter (minimum market standard) by manipulation of irrigation inputs and cut off prior to harvest. This practice should be carried out with caution as low water inputs (less than 60% replacement) and early cut off (four weeks prior to harvest) will reduce fruit size and fruit quality and delay the development of fruit peel colour.

Work carried out by the Crops, Forestry and Horticulture Division to establish water requirements of mangoes, shows that fruit size increases with increasing amounts of water up to 100% evaporation replacement. Dry matter development is delayed with increasing water inputs. The current recommendation of 70% evaporation replacement is a compromise in terms of balancing the requirements for adequate fruit size, fruit quality and time to maturity.

Further Reading

Poffley, M. (1999). Mango Management - Flowering to Market. DPIFM. Agnote D9.

Appendix One - Mango Irrigation Guidelines

Note: the irrigation rates presented in Table 1 are a *guideline* and should be used as a starting point. The actual irrigation rate should be determined for each site by the use of soil moisture monitoring methods.

Assumptions

- Crop Factor (Irrigation Replacement Rate) = 0.7
- Mean evaporation rate for Darwin and Katherine areas (July to November) = 8.0 mm/day.
- Canopy cover, expressed in m^2 per hectare (10 000 m^2) of land.

Method

1. Measure the canopy cover in your orchard as described in the following guidelines.

2. Calculate your tree density (trees per hectare).

3. Select the most appropriate canopy cover and tree density which describes your orchard in Table 1. Record the value where the grids meet. This value is your water requirement in litres per tree per week. e.g. canopy cover 5000 m^2, plant number per hectare 140. Water requirements are 1400 litres per tree per week. If your orchard statistics fall in between those listed in Table 1, select the nearest or a value in between the two extremes.

Canopy Cover Calculations

Area of circle method

Use this method when the canopy of each tree is a separate unit. For example, in young orchards and or in wide row spacing situations:

- Measure the radius of a number of trees (10) at four locations around the canopy. Average the readings.
- Use the formula, area (m^2) = pi $(r)^2$, where pi = 3.1416 and r = average radius. For example, if the average radius (r) = 2.5m; then area = pi $(2.5)^2$ = 3.1416 x 6.25 = 19.6 m^2.
- Multiply the tree canopy area by the number of trees per hectare to calculate the canopy area per hectare. For example, if you have 160 trees/ha then 19.6 x 160 = 3136 m^2/ha.

Row crop method

Use this method when the tree canopies meet within the row. Note that this method will overestimate canopy cover if the trees are only just beginning to touch. If this is the case then the 'area of circle' method is more appropriate.

- Measure the canopy width from one side of the row to the other. Do so in at least 40 sites throughout your orchard. Average the readings.
- Multiply the average canopy width by the tree spacing within the row. For example, 6.5 m (average canopy width) x 5.0 m (tree spacing in row) = 32.5 m^2.
- Now multiply the canopy area per tree by the number of trees per hectare. For example, if 200 trees/ha then 32.5 x 200 = 6500 m^2/ha.

Table 1. Average mango tree water requirements (Darwin and Katherine areas) in litres per tree per week. Based on canopy cover and tree density

	Trees per hectare						
Canopy cover m^2/ha	**80**	**100**	**130**	**140**	**160**	**180**	**200**
1000	490	390	330	280	250	220	200
2000	980	780	650	560	490	440	390
3000	1470	1180	980	840	740	650	590
4000	1960	1570	1310	1120	980	870	780
5000	2450	1960	1630	1400	1230	1090	980
6000	2940	2350	1960	1680	1470	1310	1180
7000	3430	2740	2290	1960	1720	1520	1370
8000	3920	3140	2610	2240	1960	1740	1570

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APPENDIX 2

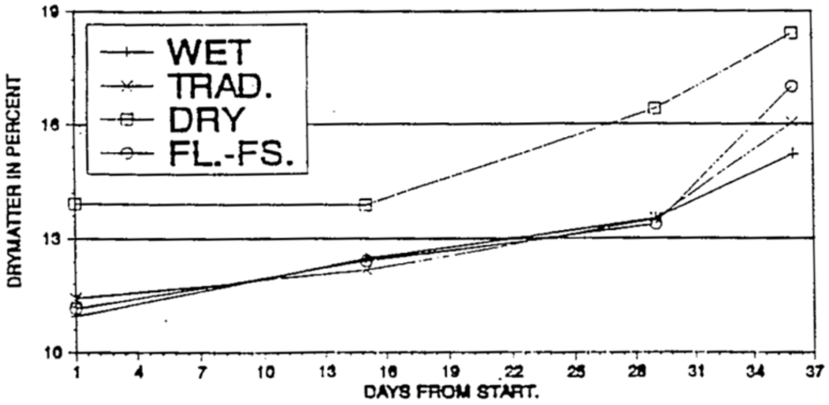

Figure 1. The percentage dry matter of fruit samples (four fruit per irrigation treatment) from 19 September (Day 0) to harvest for 'wet' irrigation from March to harvest, 'Trad.' from 50% panicle appearance to harvest, 'Dry' no irrigation and 'flower-fruit set' irrigation from 50% panicle appearance to completion of fruit-set five weeks from harvest (24 September, Day 5) for 1990 harvest of 6 year old Kensington Pride trees at Coastal Plains Research Farm, from Kuppelwiesser (1990)

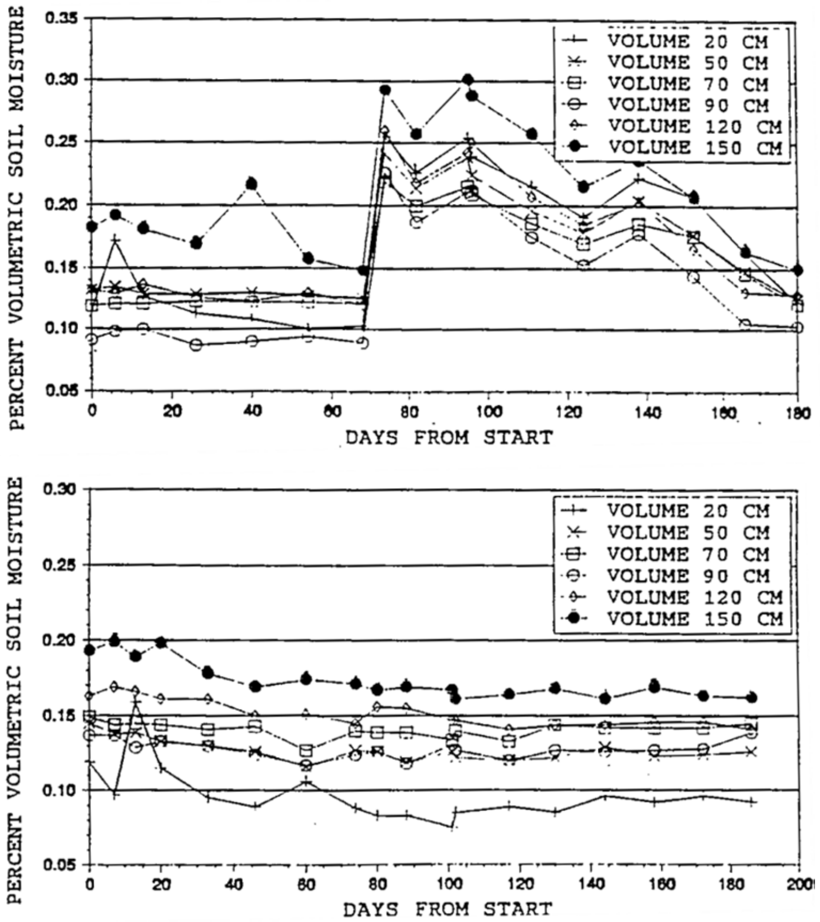

Figure 2. The percentage soil moisture from May 4 1990 (Day 1) for soil in the 'traditional' (top graph, from 50% panicle appearance to harvest) and 'dry' (bottom graph, nil irrigation) treatments, from Kuppelwiesser (1990)

APPENDIX 3

Table 1. Tree yields (kg/tree) in relation to irrigation volume and cessation timing treatments for eight-year-old Kensington Pride trees on a sandy loam, canopy cover was 60%, trees were irrigated three times a week, the trial was at Manbulloo in Katherine, from Diczbalis (1993)

	Cease irrigation, week before harvest				
Irrigation volume % of pan evaporation (l/tree/week)	**4**	**2**	**1**	**0**	**mean**
74 % (1944 l/t/w)	78.3	107.7	112.7	101.0	99.9b
59% (1555 l/t/w)	81.9	69.3	66.5	95.2	78.2a
44% (1166 l/t/w)	122.0	97.8	87.1	90.2	99.3b
30% (778) l/t/w)	62.1	79.2	66.6	52.5	65.1a
Mean	86.1a	88.5a	83.2a	84.7a	

Table 2. Fruit number per tree in relation to irrigation volume and cessation timing treatments as detailed in Table 1, from Diczbalis (1993)

	Cease irrigation, week before harvest				
Irrigation volume % of pan evaporation (l/tree/week)	**4**	**2**	**1**	**0**	**mean**
74 % (1944 l/t/w)	261	344	360	331	324b
59% (1555 l/t/w)	278	220	204	294	249a
44% (1166 l/t/w)	417	324	276	292	327b
30% (778) l/t/w)	209	255	212	171	212a
Mean	291a	286a	263a	272a	

Table 3. Final harvest brix values for fruit one week after harvest in relation to irrigation volume and cessation timing treatments for eight year old Kensington Pride trees on a sandy loam, canopy cover was 60%, trees were irrigated three times a week, at Manbulloo in Katherine, from Diczbalis (1993)

	Cease irrigation, week before harvest				
Irrigation volume % of pan evaporation (l/tree/week)	**4**	**2**	**1**	**0**	**mean**
74 % (1944 l/t/w)	17.5	16.7	16.1	16.6	16.7ab
59% (1555 l/t/w)	17.2	16.6	15.4	17.2	16.6a
44% (1166 l/t/w)	16.4	16.2	16.4	16.8	16.5a
30% (778) l/t/w)	16.9	17.9	16.6	18.5	17.5b
Mean	17.0b	16.8ab	16.1a	17.3b	

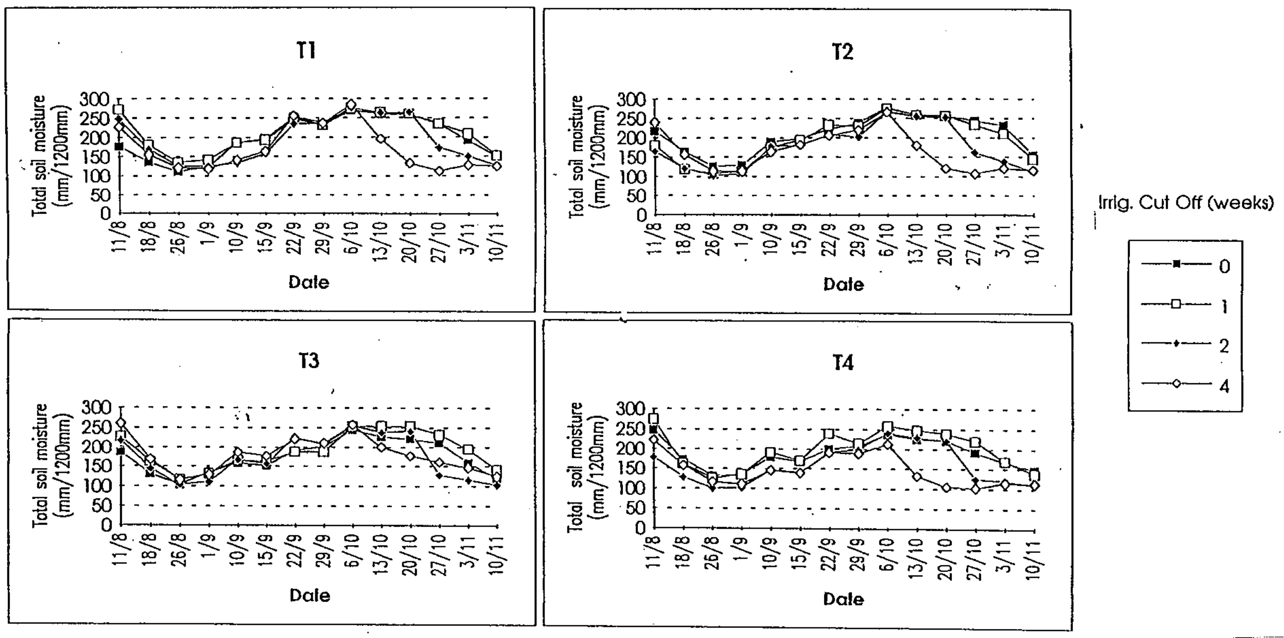

Figure 1. The total soil moisture from 11 August 1992 to harvest for four irrigation volumes, T1 1944 l/tree/week, T2 1555 l/tree/week, T3 1166 l/tree/week, T4 778 l/tree/week and four irrigation cessations (cut-off) at 0, 1, 2 and 4 weeks before harvest, from Diczbalis (1993). A pump breakdown from 10 to 22 August at the start of the trial was noted as causing a dry period across all treatments.

APPENDIX 4

Table 1. Fruit dry matter (%) in relation to irrigation volume and cessation timing treatments, from Diczbalis et al (1994b)

	Cease irrigation, week before harvest				
Irrigation rate % of pan evaporation (L/tree/week)	**4**	**2**	**1**	**0**	**mean**
100% (2400 L/t/w)	19.97	18.66	19.30	18.89	19.20c
80% (1920 L/t/w)	18.93	18.78	18.83	18.54	18.77b
60% (1440 L/t/w)	19.56	18.91	19.42	17.53	18.85bc
40% (960) L/t/w)	18.39	17.97	17.75	17.49	17.90a
Mean	19.21c	18.58b	18.82b	18.11a	

Table 2. Irrigation treatments 40% and 100% of pan evaporation (as presented in Table 1) for number of days to eating-ripe and skin colour rating (1 = fully green, 6 = fully coloured), from Diczbalis et al (1995a)

	Days to eating-ripe		Skin colour	
Days after panicle emergence	**40%**	**100%**	**40%**	**100%**
76	16.5	17.4	2.9	2.9
83	10.7	10.7	3.3	3.8
89	10.5	9.0	4.1	4.7
96	9.4	9.4	4.4	4.9
103	8.1	7.6	4.6	5.1

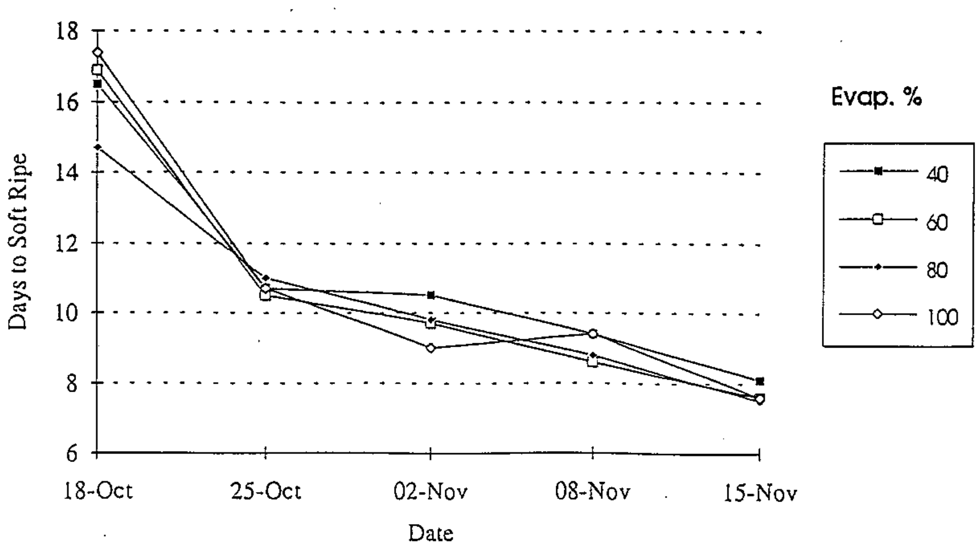

Figure 1. Days to soft ripe from harvest in relation to time and irrigation treatments, from Diczbalis et al (1994b)

APPENDIX 5

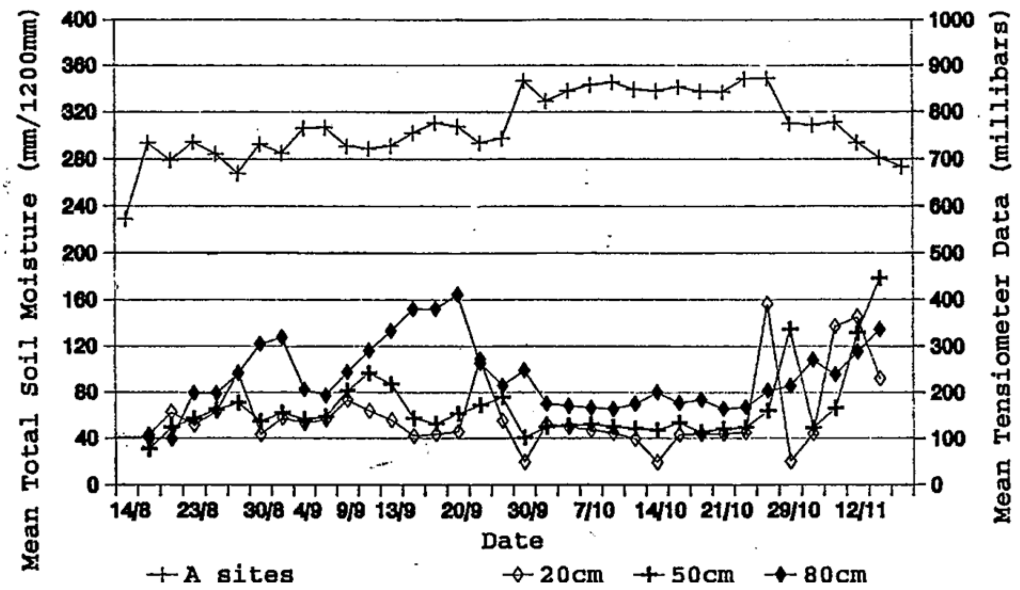

Figure 1. The total soil volumetric moisture (left hand side axis) to depth of 1.2 m and mean soil tensions (for 20, 50 and 80 cm depths) from mid August 1991 to harvest for a commercial mango orchard, from Diczbalis and Bowman (1991)

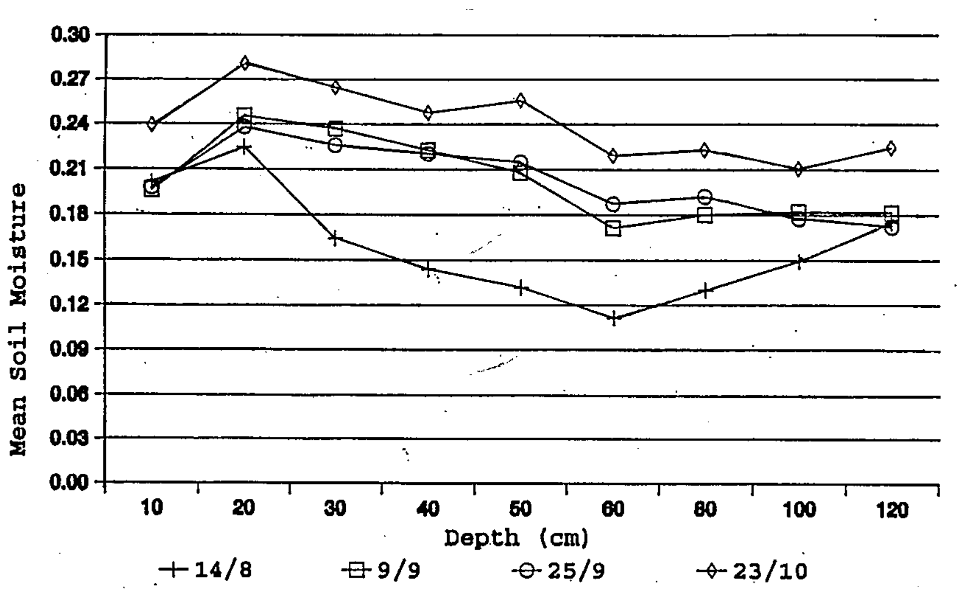

Figure 2 .The mean volumetric moisture (water cm^3/soil cm^3) at nine profiles for four dates during the monitoring period, from Diczbalis and Bowman (1991)

APPENDIX 6

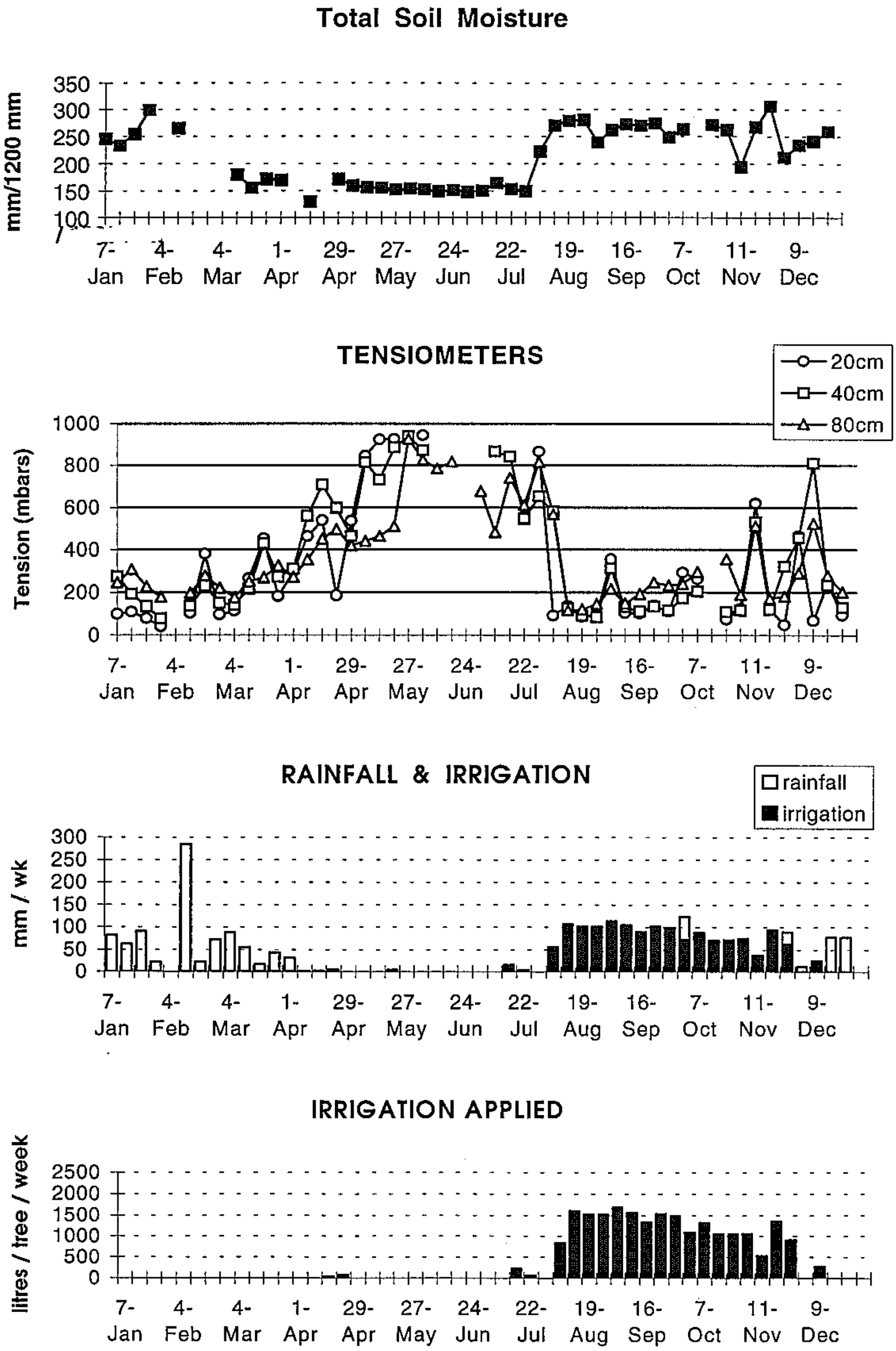

Figure 1. Weekly total soil moisture (top graph), soil tension (second from top), rainfall and irrigation (mm/week) (third from top) and irrigation also as l/tree/week (bottom graph) for a commercial mango orchard in the 1993 season, from Diczbalis et al. (1995b)

APPENDIX 7

Table 1. Predicted harvest dates based on the heat sum calculations for three NT cropping locations and five flowering dates. The heat sum used [(daily max temp + daily min temp)/2] - 12 predicts the timing of maturity defined as a dry matter of 14%. The temperature data was based on a 10 year running average (sourced from BOM)

	Location		
Flowering date	**Darwin**	**Berry Springs**	**Katherine**
1 May	26 Aug	4 Sept	16 Sept
1 June	24 Sept	1 Oct	7 Oct
1 July	18 Oct	21 Oct	24 Oct
1 August	10 Nov	12 Nov	9 Nov
1 September	5 Dec	5 Dec	28 Nov

APPENDIX 8

Table 1. Summary of two water use efficiency studies, Spreer et al. (2009) results are means of three study seasons (rainfall during irrigation, 70, 333 and 105 mm in each of three seasons) on variety Chok Anan including a partial root zone drying (PRD) and da Silva et al.(2009) results are the mean of two study seasons on variety Tommy Atkins (mean rainfall during irrigation, 154 mm each season), ET_p = potential evapotranspiration

Study	Treatment	Irrigation applied, m^3 tree	Yield (kg/tree)	WUE, kg yield/ m^3 water
Spreer et al. (2009)	100% ET_p	3.2	23.5	7.4
	50% ET_p	1.7	23.7	14.1
	50% PET ET_p	1.6	22.9	14.1
	Nil irrigation	0	20.1	-
	Treatment	**Irrigation applied, mm**	**Yield, t/ha**	**WUE, kg/ha/mm of irrigation**
da Silva et al.(2009)	100% ET_p	549	28.1 c	51.1
	90% ET_p	478	31.1 ab	65.0
	80% ET_p	413	30.0 a	75. 6
	70% ET_p	366	29.5 a	80.7