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Horticulture Australia Limited

Final Report

Nutrition and irrigation requirements for the Queensland papaw industry (Full Report)
(Project FR405)

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Queensland Department of Primary Industries and Fisheries

HAL FR405: Nutrition and irrigation requirements for the Queensland papaw industry

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Objective of project:

Develop more sustainable nutrient management strategies for papaya production in north Queensland by reviewing the literature on fertilising practices, determining plant uptake and nutrient removal of macro-nutrients in papaya, assessing the utility of quick test petiole sap analysis methods and evaluating the effect of different rates of nitrogen and potassium on productivity and fruit quality.

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EXECUTIVE SUMMARY

INDUSTRY SUMMARY

Irrigation
Studies with soil monitoring equipment in papaya blocks in three different soils (a sand "Toolakea", a clay "Mundoo" and a silty clay "Innisfail") provided some useful results. The major findings were:

It is best to use both field studies and laboratory data to establish the full and refill points for irrigation management of soils. For the sand at Etty Bay, the full point was established at -8 kPa and 11.8% volumetric water content. For the Innisfail silty clay, the full point was established as –18 kPa and 39.5% moisture content, whilst for the third soil, Mundoo clay (Krasnozem) the full point was set at –15 kPa and 36% moisture content.

Refill points were established also for the three soils above and concluded for the sand values of –20 kPa and 10.3% moisture content; for the silty clay –60 kPa and 27.5%; for the clay soil –60 kPa and 27% moisture content.

The PAWC (plant available water capacity) for papaya irrigation was calculated for each of the soils and established 48 mm for the Innisfail silty clay, 36 mm for the Mundoo clay and 6 mm for the Toolakea sand, per 40 cm depth of soil. The majority of roots for papaya were found in the top 40 cm of soil, and this was used to determine the range of PAWC.

Thus for each soil type, two sets of numbers were produced to assist with irrigation scheduling. The full point is used to determine how much water the soil can hold without significant drainage losses out of the design root zone (40 cm). In contrast the smaller number, the refill point determines the lowest level that can be reached before plant stress commences. If your soil is wetter than the full point you might waste water and nutrients through drainage and leaching; if your soil is drier than the refill point you might suffer yield losses or incur fruit quality problems.

To use the refill and full point volumetric data, you need either a Neutron Probe, an Enviroscan, or a Time domain Trase system. These systems are all expensive and sophisticated, but once learned are quite easy to use and provide accurate information quickly. For smaller scale operations, a tensiometer based system is more practical, such as the Soil Spec system which uses an electrical transducer/meter to measure moisture potential from multiple tensiometers. Alternatively, a Star Logger system could be used or gypsum blocks.

Studies were completed to measure wetting patterns and water movement laterally and vertically through the soil, using the clay Mundoo soil type, and sprinkler (40L/hr), button dripper (8L/hr) and drip tape 9L/hr/plant outlets. The sprinkler wetting patterns varied a lot and were much wetter at 50 cm from the plant than at 1m from the plant. Water from sprinklers was found to move quickly through the soil at about 20cm distance from the plant, but much slower elsewhere.

This is due to either poor sprinkler distribution uniformity or the effects of mounding cross-sectional slope changes, or both. The button drippers wet the soil very fast at the rate of 25 to 50 cm depth of wetting per half-hour, and would be even faster in a sand. The drip tape wet the soil quickly to about 25 cm depth per hour. Under driptape the maximum strip width of 50 cm was achieved in 2 hours, and for drippers the maximum circle area of 0.25 m^2 was achieved in 1.5 hours.

The large irrigation field trial at the South Johnstone Research Station, showed that best results for Mundoo clay soils were obtained using shared sprinklers with two plants. Next best results were obtained using double drippers per tree, single driptape then double drip tape. Worst results were obtained with a single dripper per plant, at the low rate of irrigation. The average weekly irrigation water requirement to maintain high yields was 70 L/tree per week, but was much higher than this in hot dry periods. The actual maximum weekly range was from 36 L/Tree for double drippers, 50L/tree for single driptape and 169 L/tree for shared sprinklers. These rates are well within the lower ranges as compared to benchmark survey results. At least half of growers are likely thus to be over irrigating at peak times, and nothing is stated about irrigation in other times.

Some trees were dug up after the trial finished to examine root systems. Sprinkler irrigated trees generally had a more open, less branched root structure, than did drip irrigated trees, which exhibited larger numbers of smaller roots, and appeared more matted. All root systems were located mainly in the top 30 cm of soil with only 1 or 2 roots extending to a maximum of 1.2 m depth.

Nutrition Management

We investigated the effects of different rates of application of nitrogen and potassium fertilisers on the growth and yield of papaya at South Johnstone from 1995 to 1997. We wanted to answer the question "How much nitrogen and potassium do papaya plants need to optimise yield, fruit quality and sustainability of production."

Optimum yields were obtained with nitrogen fertiliser rates of 300kg N/ha/21 months (≈170kg/ha/yr) and 574kg K/ha/21months(≈328kg/ha/yr). These rates were about half that of the industry average when surveyed in 1995 . Plant analysis of leaf petioles suggest an adequate concentration of 1.05% for N and 3.5% for K. This was largely unaffected by sampling time. Petiole sampling should consist of 20 whole petioles /ha (1.2% of trees). Plant sap quick test methods (i.e. RQ Flex reflectometer) can also be used to monitor N and K status to more efficiently apply fertilisers, particularly during the first 8 months after planting. Tentative adequate concentrations in petiole sap were nitrate N 35mg/l and K 2.4g/l. The adequate level for soil nitrate N was determined as 40mg/kg but because individual applications of N fertiliser has a big impact on soil nitrate levels this makes such monitoring very difficult to utilise.

TECHNICAL SUMMARY

Irrigation

Studies designed to measure the responses of papaya plants to different soil moisture regimes, different wetted areas and volumes, and in different soil types were conducted from January 1996 to June 1997, in North Queensland. A major irrigation trial was established in the Mundoo series soil type near SJRS, and studies were completed on a Toolakea series beach sand at Etty Bay, and an Innisfail series soil at SJRS.

Tensiometer μ_s particularly in the -10 to -20 kPa, range recorded in conjunction with derived non significant drainage rates of 1 to 2 mm/day, were found to be useful in setting upper storage limits (USL) for soil water management. Laboratory measurements of μ_s at -5 kPa overestimated USL, and at -10 kPa over or under estimated USL. Drainage of the Innisfail soil was comparatively slow, the Mundoo soil fast, and the sand rapid. Tensiometer μ_s at -33 kPa was always an underestimate of the USL. For the Toolakea soil refill point was found to be at -8 kPa and 11.5% volumetric water content; the Mundoo soil at -15 to -20 kPa and 35.6%; and the Innisfail soil at -15 to -20 kPa and 39.5% volumetric water content.

Conventional methods for determining plant water status of papaya plants were not successful in this study due either to equipment unreliability or uncertainty relating to plant responses to applied methods. However, the determination of derived relative fruit volumes (RFV) from stressed and watered plants did prove to be a useful indicator of plant water stress, such that when stored soil moisture declined below the lower storage limit, RFV decreased rapidly.The lower storage limits were derived by considering soil matric potential changes and changes in fruit volumes in relation to decreasing soil water contents, which gave PAWC much lower than the calculated AWC for both soils. PAWC based upon 50% depletion of AWC overestimated PAWC for the Toolakea sand, and gave similar PAWC for the Mundoo clay, in comparison with refill point derived PAWC. The Mundoo PAWC calculated at 0.088 mm water/ mm soil , was close to the commonly used 50% depletion concept, and also much lower than the AWC. The calculated PAWC for the Toolakea soil was 0.0137mm /mm soil. For the Innisfail series soil, total reliance upon the 50% depletion was required due to lack of plant response data, and PAWC was set at 0.125 mm water/ mm soil. PAWC based upon laboratory retention data at -10 kPa and PWP grossly exaggerated PAWC for both soils and highlights the limitations of such laboratory determinations.

Studies on selected sprinkler and emitter flow rates into soils established:

- sprinkler wetting patterns are notoriously variable and the gross precipitation rate should be used or the mean of catch cans radially from the sprinkler. Close to the sprinkler (<50 cm) wetting front movement to 50 cm was achieved in about 1 hour, at distance >50 cm the soil was not saturated beyond 20 cm depth even after 2 hours of irrigation.

- Single button drippers (8L/hour) wet the soil faster at 15 rather than 30 cm radially from the emitter, and after 1 hour, the soil was saturated to 50 cm depth 15 cm from the emitter and after 2 hours to 50 cm depth, 30 cm radially from the emitter. Single button drippers have high precipitation rates and thus the potential for drainage losses is high unless carefully monitored. For single drip tape the wetting front moved to 50 cm in about 2 hours, and for double drip tape the wetting front reached 50 cm in about 2.5 hours. The drip tapes have slower precipitation rates than drippers and thus less likely to cause localised drainage losses. Maximum wetted areas are achieved after 1 hour of irrigation for all the emitters. For 8L/hour button drippers, irrigation duration should not exceed 1 hour duration, and for drip tape >2 hours, on soils of similar porosity to that studied. For sprinklers the gross precipitation rate (litres/hour/wetted area) should be used to determine irrigation duration.

- Rate of irrigation as determined by replacement of water at 50% and 100% depletion of PAWC, did affect papaya yield but not growth and fruit quality. The amount of water applied total was significant in yield responses, with an increase in yield up to 2500 litres per tree, which was found to be equivalent to a mean weekly application of 70 litres per tree. The optimum wetted area as achieved by different irrigation systems was found to be about 1 m^2 per plant, although highest yields were attained with shared sprinklers wetting 3.5 m^2 area per plant. The best model to describe yield was found to be related to tree girth, rate of precipitation and soil water storage limits, which collectively described 90% of total yield variation. Tree size was well related, non-linearly to water applied per tree with little change in size beyond 1500 litres per tree.

- Although many yield differences across treatments were only marginally significant, a comparison of agronomic, water usage, drainage and gross margins per hectare of all treatments revealed the best overall irrigation system to be shared sprinklers at the low irrigation rate, followed by double drippers and single drip tape, for the soil studied. Differences due to irrigation rate were minimal partly due to the difficulty in imposing watering regimes over a shallow rooted crop. Drip tape responses were not fully evaluated due to the erratic yield obtained in alternative plots of two treatments. The single drippers at low rates were by far the least desirable system, and single drippers at high rates although rated third overall, would seem to be more risky where irrigation scheduling is not accurate and timely. The large wetted area and water application rates of individual sprinklers per tree are wasteful of both dollars and water.

- Evidence of root studies and excavations showed differences in root systems in response to irrigation system, such that sprinkler irrigated trees generally had a more open, less matted root architecture than either dripper or drip tape irrigated trees. All systems suggested strongly that roots are concentrated in the upper 30 cm of soil with tap roots extending to up to 1.2 metres depth.

Nutrient Management

Applied nitrogen at medium to high rates was associated with significant reductions in soil pH, and optimal yield was achieved at application rates of 300 kg/ha of N over a 21 month period. This was about half the industry average at the commencement of the study. There were no effects of N on fruit quality. Potassium at higher rates (>500 kg/ha of K) significantly increased yields but had no effect of significance on fruit quality. Only weak non-linear relationships of yield and petiole N concentrations were obtained, suggesting an adequate concentration of 1.05%. For potassium a similar lack of response was established with an adequate level of 3.5% in petioles. Sampling time in mature papaya had no effect in improving the relationship of both N and K with yield. Nitrogen balance audits indicated a large unaccounted amount of N at rates of application exceeding 300 kg/ha.

Results from NQ suggest that both N and K may suffer from reduced concentrations at sampling intensities as currently employed. For this reason it is recommended, that at least 20 petioles per hectare or equivalent intensity of sampling be used for papaya foliar analysis, and this would cover the requirements of all the macro-nutrients. At 20 petioles per hectare, about 1.2% of trees would be sampled, and this seems to be more representative than using 0.6% of trees with 10 petioles per hectare. It is recommended to use the whole petiole for sampling, before sub-sampling for analysis, and that leaf blades are not used.

Good relationships of petiole sap nitrate N, sap K with laboratory data, the sensitivity to detect differences in fertiliser applications and reasonable yield relationships (Nitrate N, $R^2 = 0.53$) have established the potential for using reflectometers to monitor N and K plant nutrient status, and obtain possible indications with P status. Tentative adequate concentrations in petiole sap are Nitrate N 35 mg/L, K 2.4 g/L, and P 118 mg/L.

The adequate level for soil nitrate N RQFlex was determined as 40 mg/kg and was well related to laboratory determined nitrate and reflected the range of applied N fertiliser across treatments but because individual applications of N fertiliser has a big impact on soil nitrate levels this makes such monitoring very difficult to utilise.

The importance of stems and fruits of papaya as storage organs for all the macro-nutrients is apparent from this study, as is the high requirements for K by papaya plants particularly in roots and fruits. The high rate of fruit production by papaya crops (135t/ha/year) means that subsequent removal of this harvested fruit draws large quantities of nutrients from the plant/soil system. Fruit nutrient removal at maturity, equates to 46% of total uptake and removal for K down to 23% for Ca, with other nutrients in between. There is no doubt thus that the nutrient requirements of papaya under tropical, irrigated management are high. But results from the papaya nutrition trial indicated that rates of applied N above 300 kg/ha and applied K above 574 kg/ha does not increase yields.

By using fortnightly sap test methods it should be possible for growers to schedule N applications to young papaya plants, based upon growth measurements and tentative threshold levels of about 35 mg/L petiole sap nitrate N, working from a basal program of applying 5g N per plant per month up to age of about 8 months for a total of 40 g/plant. This is equivalent to 67 kg/ha N over 8 months (196 kg/ha ammonium nitrate).

IMPLICATIONS FOR SOIL WATER MANAGEMENT

A synthesis of results obtained in this study allows the defining of suitability of two distinctly different soils, a clay (Mundoo) and a beach sand (Toolakea) for different irrigation systems, and operational limitations, in conjunction with papaya irrigation. The following is assumed:

- papaya plants require on average 70L per plant per week
- PAWC for clay 36mm/40cm; for sand 6 mm/40 cm
- Rooting depth 40 cm
- sprinklers at 40L/hr (shared for 2 trees), gross precipitation rate P of 6 mm/hr
- driptape 9L/hr per plant, P of 18 mm/hr
- drippers 8L/hr, P of 38 mm/hr
- wetting front movement estimated at 10 cm/hr for sprinklers, 25 cm/hr for dritape, 50 cm/hr for drippers. For sand will be faster than this. Wetting front advance is dependent upon initial soil moisture profile, hydraulic conductivity and rate of precipitation from the outlet.

	Irrigation hours to fill soil to full point, from refill point	**Max. irrig duration , hrs to avoid drainage (safe irrigation)**	**Irrig. Volume delivered, L per safe irrigation / plant**	**Number of safe irrigations to deliver 70 L/plant**	**Suitability for papaya irrigation**
Clay					
=with sprinkler	6	4	80	1	Good
=with dripper	1	0.75	6	12	OK- needs pulsing or daily watering
=with driptape	2	2	18	4	Good
Sand					
=with sprinkler	1	1	20	4	Good
=with dripper	0.15	.15	1.2	58	Incompatible
=with driptape	0.33	.33	3	23	Marginal – better to use two lines of tape

For a sand, the above data illustrate for papaya irrigation, the very low PAWC and the high gross precipitation rate of drippers are incompatible, and if used would require extremely frequent short pulses of 20 minutes, and may not be able to supply a sufficient quantity of water into such a small volume of soil wetted. For such a soil/ crop combination sprinklers are ideally suited, as long as operating times don't greatly exceed 1 hour. For the clay soil with its larger PAWC and lower expected hydraulic conductivity, the range of options are greater. This is particularly so for these well drained, deep, porous Krasnozem soils on the wet tropical coast of NQ. It will not however be the same for all clay textured soils; those clays with poorer structure and less sand or with swelling capacity, will tend to have a lower conductivity thus they may be better suited to sprinkler irrigation only.

RECOMMENDATIONS

EXTENSION PROCESS FOR ADOPTION/TRANSFER

Irrigation
A series of interactive workshops and field days aimed at achieving an understanding and awareness of:

- Full/Refill points in the three soils and the usage of tensiometers and other instruments to schedule papaya irrigation
- Discuss and demonstrate wetting patterns and wetting front movement under three different outlets: drippers, driptape, sprinklers. Vary line pressures to record P rates and flow rates; use catch cans to record sprinkler distribution uniformity.
- Introduce concepts and principles of Integrated Irrigation Management
- Highlight and expand major findings of the irrigation systems trial

Nutrient Management
Extension process for adoption/transfer
The findings from this work indicate that the rates of nitrogen and potassium fertiliser to obtain optimum yield of papaya are dramatically lower than conventional practice. Growers will perceive that there is significant risk of reduced yields associated with the direct adoption of these findings particularly with several industry representatives believing that the plants in the trial were growing poorly even though yields obtained in the trial were comparable to industry standards. What is needed is to have at least 2 development trials on grower's properties (1 on krasnozem, 1 on sands) to implement the findings of our work in conjunction with best-bet management procedures. Ideally these development trials should have conventional practice (including high N & K rates) alongside to assist in authenticating to growers the value to them of the research findings. There may be a relationship between higher rates of nitrogen fertiliser and reduced capacity of disease defence. This should be monitored during such trials on growers' properties. In conjunction with these development trials which would involve several field walks, a series of extension articles would be produced mostly for Papaya Post including an 8 page information bulletin which interprets the results from field experiments and formulates revised crop nutrition strategies for the north Queensland papaya industry.

DIRECTIONS FOR FUTURE RESEARCH

Irrigation
The effort should focus resources into the development and adoption of irrigation management and training for growers. This would entail "on farm" or "soil type" research and development projects to elaborate full points, refill points and PAWC. The overall emphasis to be on promoting irrigator awareness, understanding, involvement and adoption of improved irrigation management techniques.

Nutrient Management

Future research needs will be largely driven by the progress of the development trials and the needs identified by this on-farm work. However, one thing is clear - future papaya R & D will need to focus on competitive and sustainable production systems. The papaya industry needs to improve its international competitiveness because of threats from imports and crop management systems require change to comply with environmental guidelines and market expectations whilst remaining strongly competitive. Such production systems research requires a high level of integration of the R & D effort so a more coordinated approach for the delivery of R, D & E which maximises the synergy among all participants is required.

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CHAPTER 1: GENERAL INTRODUCTION

1.1 THE PROBLEM: HOW MUCH WATER DO PAPAYA'S NEED AND HOW OFTEN

In common with many horticultural crops, the irrigation requirements for ecologically and economically sustainable papaya (pawpaw, *Carica papaya*) production, have not been established and growers operate in an information vacuum. There is no data relating water usage and yield and fruit quality, and this issue was of particular concern to the industry. This project was established in conjunction with an investigation of papaya nutrient requirements, to determine irrigation and nutrient management practices associated with optimum fruit yield and quality, and the promotion of sustainable industry development in Queensland.

1.2 LITERATURE REVIEW

The data and studies relating papaya water usage, irrigation and crop development are few in number. Awada *et al.*(1977) established optimum yield of papaya (132kg/tree) in Hawaii at a mean of 93L/tree split twice per week through drip emitters. In Nigeria Aiyelaagbe *et al* (1986) investigated the response of papaya to soil moisture potential and established the –200 kPa treatment as the lower stress level or refill point. These authors established that plants stressed to –600 kPa did not carry fruits.

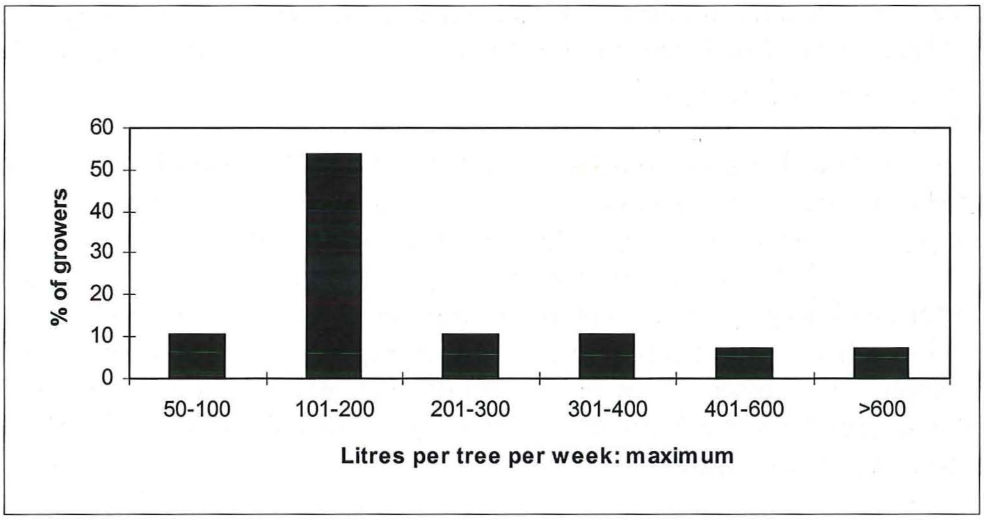
Fruit quality was not affected by a range of soil moisture regimes in India (Jayaprakash *et al.* 1989) but reported yields were very low at 35 kg/tree. In Peurto Rico, daily mean water usage was calculated to be 3.6 mm/day based upon the modified Blaney-Criddle model of plant evaporation (Goyal 19, J.Agric. Puerto Rico). In Malaysia Masri *et al.* (1990) found reduced growth increments and drastically reduced numbers of flowers and fruits in plants growing in soils with a moisture potential more negative than -50 kPa.

1.3 BENCH-MARKING OF QUEENSLAND PAPAYA INDUSTRY IRRIGATION PRACTICES

A survey of grower irrigation practices was completed in 1995 by Richards *et al.*, for major growing areas in North (NQ), Central (CQ) and South East Queensland, (SEQ). In NQ 90% of growers use under tree micro-sprinklers to deliver water, commonly sharing one sprinkler over 4 trees. All growers surveyed in NQ used irrigation. This was not the case in SEQ where irrigation in the Gunalda area is not generally used, due to lack of water. In CQ irrigation is commonly used, mainly with drippers or drip-tape. In SEQ all types of systems are used, including portable overhead sprinklers on steep, rocky slopes.

Figure 1 summarises the distribution of applied irrigation water at maximum output in North Queensland papaya farms. The most common rate is about 100-200 litres per tree per week during peak periods, with the maximum over 600 litres per tree per week. Irrigation is carried out through the year and stops only during intense, prolonged raining periods. In NQ the average maximum irrigation period is 18 hours per week, delivering about 30mm per tree per week. In SEQ a rough usage indicated about 8.5 hours irrigation per week at peak requirement, delivering about 25mm per tree per week. Equivalent data estimates are not available for Central Queensland.

Figure 1: Irrigation output distribution of North Queensland Papaya Farms.



Understanding and awareness of irrigation scheduling and related issues of soils used for papaya and other fruit production in the coastal wet tropics of North Queensland (NQ) is generally poor. The papaya industry is a large water user (approaching 600 Kilolitres /ha /week at peak consumption over 600 ha) , despite high annual rainfalls in excess of 3 metres. The survey also revealed that 65% of growers relied upon soil colour, 49% relied upon plant stress symptoms, and 46% used recent weather patterns to make irrigation decisions. The range in maximal water application rates varied from 50 to >600 litres per tree per week as indicated in Figure 2.

Figure 2. Distribution of irrigation water usage by papaya growers during peak periods.

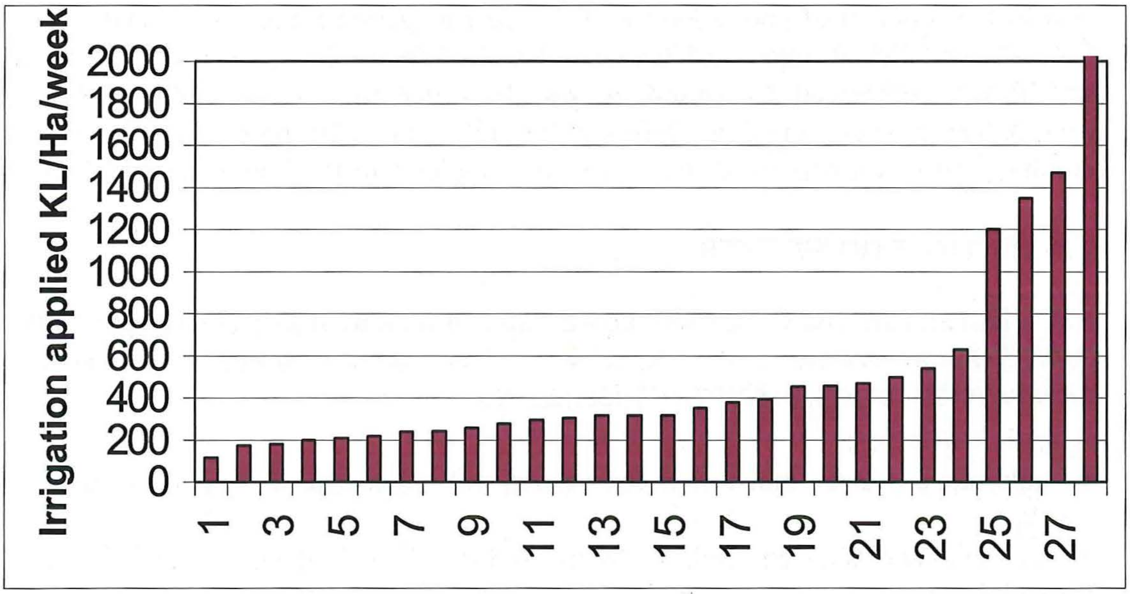


Figure 2 highlights the variability in irrigation applications, with 5 growers applying <200 KL/ha (approximately 120 L/tree) and 10 growers applying more than 400 KL/ha. One grower was reportedly applying upto 3100 KL/ha. Overhead sprinklers were used by 5% of growers as were drippers or drip tape. The remaining 90% of growers used under tree micro sprinklers in various arrangements of interrow and sprinkler spacings. Most growers (55%) obtain water from local rivers, while some 32% pumped from underground bores. The remainder either pumped from irrigation channels (Mareeba Dimbulah Irrigation Area) or from swamps and springs. Only 10% had taken a water quality test.

The wet tropical coastal region from Cairns in the North to Cardwell in the south, produces 85% of Queensland papaya production annually which equates to about 80% of Australian production. Despite high annual rainfalls irrigation is required throughout the year. This is a consequence of fast growth rates of papaya, soils used are often porous and deep draining, planting is on raised beds about 40 cm high, and many rainfall events are not effective due to high precipitation rates and associated runoff. Irrigation is thus essential for production of many plants in this wet tropical region, and both growers and government agencies give irrigation management alike, outside of the major irrigation areas.

The problems associated with poor adoption of integrated irrigation management can be grouped into resource based, information based, attitude based and benefits based. In the North Queensland case the major factors mitigating against adoption include: many shires are in unproclaimed groundwater areas with little quantification of groundwater usage; a high annual rainfall encourages a sense of infinite water resources amongst many irrigators and the notion of cheap water; the role and resources directed by government departments has been inadequate and weakly pursued; soil water management data is incomplete or absent; there is a severe lack of water requirement data of tropical tree crops; irrigation designers are generally interested or experienced in installation only; only one consultant offers some form of dedicated irrigation management service.

Part of the problem of poor adoption of correct irrigation scheduling, relates to the lack of established upper and lower soil water storage limits in a range of soils, specifically referenced to various crops. In order to overcome this deficit of knowledge, studies aimed at defining the full and refill points for three soils, commonly used for papaya production, were completed in 1997, and reported herein.

1.4 PROJECT OBJECTIVES

1.4.1 DETERMINE THE UPPER AND LOWER SOIL WATER STORAGE LIMITS AND THUS PAWC (PLANT AVAILABLE WATER CAPACITY) FOR 3 SOILS COMMONLY USED FOR PAPAYA PRODUCTION, IN NORTH QUEENSLAND.

Specific objectives:

- calibrate a neutron moisture meter against soil volumetric water content for 3 soil types
- evaluate laboratory and field methods used to establish upper storage limits for 3 soil types

- evaluate porometry, pressure bomb, relative water content techniques, and fruit growth changes to assess the onset of papaya water stress

1.4.2 DEVELOP SOIL WATER MANAGEMENT GUIDELINES BASED UPON ROOT DISTRIBUTION AND OUTPUT CHARACTERISTICS OF EMITTERS AND SPRINKLERS.

Specific objectives:

- assess the extent of root system development laterally and vertically under different emitters and sprinklers
- establish effective irrigation design depths for papaya irrigation
- estimate the rate of soil water movement under different emitters and sprinklers and assess drainage loss risk.

1.4.3 EVALUATE PAPAYA RESPONSES, ECONOMIC PERFORMANCE AND SUSTAINABILITY UNDER DIFFERENT IRRIGATION SYSTEMS.

Specific objectives:

- determine papaya yield, growth and fruit quality responses to variations in wetted soil area and volume of water
- define the minimum wetted area and volume of water per plant required, for optimal production
- evaluate economic performance of papaya under different irrigation systems
- assess the risk of drainage loss under different irrigation systems

1.4.4 STIMULATE AWARENESS AND UNDERSTANDING OF IRRIGATION SCHEDULING AND SOIL WATER MONITORING OPTIONS OF PAPAYA GROWERS.

Specific objective:

- conduct field days and workshops to introduce and develop soil water management issues.

CHAPTER 2: FULL POINTS FOR IRRIGATION MANAGEMENT OF THREE COMMONLY USED SOILS FOR PAPAYA PRODUCTION.

2.1 INTRODUCTION

Understanding and awareness of irrigation scheduling and related issues of soils used for papaya and other fruit production in the coastal wet tropics of North Queensland (NQ) is generally poor. The papaya industry is a large water user (approaching 300 Kilolitres /ha /week at peak consumption), despite high annual rainfalls in excess of 3 metres. A survey of papaya growers practices in 1995 conducted by Richards *et al.* (1995) revealed that less than 20% of growers used soil moisture sensors in irrigation scheduling and all had no knowledge of available soil water capacities. The survey also revealed that 80% of growers relied upon experience, soil colour or plant stress symptoms to make irrigation decisions. The range in maximal water application rates varied from 50 to >600 litres per tree per week.

Gardner, (1988) gave a good overview of the problems of determining upper and lower storage limits of soil moisture (known also as full and re-fill points), in a range of soils both swelling and non-swelling. He concluded that upper storage limits (USL) were best derived using a field drainage test, which allows integration of all soil physical properties to arrive at the critical drainage rate associated with the USL moisture profile, in conjunction with soil moisture retention data. The USL represents the water content above which soil drainage out of the root zone is appreciable, and is loosely referred to as field capacity. Leuning and Talsma (1979) modeled drainage flux against time after saturation of field sites, using tensiometers and a neutron moisture meter (NMM) to measure changes in the soil, to arrive at a moisture profile corresponding to reduced drainage rates.

Conventionally, available water capacity in soils (AWC) has been arbitrarily determined as that water held between either -10 kPa or -33 kPa matric potential (field capacity) and the -1500 kPa permanent wilting point (PWP). Such results are typically derived using ground or core samples in laboratory methods, and suffer from small sample size and fabrication in sample preparation for equilibration. Reid *et al.*(1984) and Gardner *et al.*(1981) discuss the commonly poor agreement between field and laboratory estimates of AWC.

The objective of this study was to determine appropriate USL's for three common soils used for irrigated horticulture in NQ, by monitoring soil water drainage profiles and soil moisture retention.

2.2 MATERIALS AND METHODS

2.2.1 DETAILS OF SOIL PHYSICAL PROPERTIES AND SERIES STUDIED.

Soils from three series (Table 1) commonly used for irrigation in NQ were studied. The Innisfail series soil was studied at the South Johnstone Research Station (SJRS), the Toolakea series beach sand at Etty Bay south of Innisfail, and the Mundoo series krasnozem soil located 1km from SJRS. Soil series were identified by consulting a soils map and by determining soil colour and texture, as outlined by Murtha and Smith (1994).

Table 1: Particle size data and physical properties of three NQ soils studied.

Depth (cm)	Clay (%	Silt (%	Total sand (%	Bulk densi (g/cm3)	Porosity (%	θv (%) at -5 kPa	θv (%) at -10 kPa	θv (%) at - 150 kPa
Innisfail series								
0-20	51	26	23	1.26	52.5	41.7	38.7	16
20-40	56	27	17	1.33	50.0	42.2	39.6	17
40-60	53	30	18	1.39	47.6	42.1	40.0	15
60-80	49	32	20					
80-100	48	28	24					
115-125	47	24	29					
140-150	47	19	34					
(Beach sand) Toolakea series								
0-20	5	2	93	1.53	0.42	13.1	10.4	2
20-40	8	3	89	1.55	0.42			
40-60	8	3	89					
60-80	7	3	91					
80-100	6	2	92					
115-125	5	2	93					
140-150	5	2	93					
(Krasnozem) Mundo series								
0-20	68	17	15	1.26	52.5	42.2	40.5	22
20-40	76	15	10	1.27	52.1	43.0	41.1	23
40-60	77	13	10	1.33	49.8	45.0	43.2	24
60-80	77	12	10	1.33	49.8	44.3	42.5	24
80-100	79	12	10					
115-125	79	12	9					
140-150	77	13	10					

All sites have a history of cultivation of bananas or papayas. The study was conducted from August 1995 to January 1996. The particle size analysis (PSA) data was determined by the method of Gee and Bauder (1986) in the QDPI laboratory in Mareeba, NQ. Bulk density and soil moisture potential measurements were derived using steel sampling rings (volume 210 ml) inserted with a modified ramset press device at depths of 20, 40, 60 and 80 cm for Mundoo soil, 20,40 and 60 cm for Innisfail soil, and 20 and 40 cm for the Toolakea soil, as there was little change in soil texture in all soils below 60 cm depth. Saturated cores were equilibrated with -10kPa and -5kPa (-33 kPa not available) tensions using a suction table apparatus, and PWP moisture retention obtained by equilibration at -1500 kPa on a pressure plate. Data on pore space relationships and retentivity were collected from major rooting zones and for the sand in 1 layer only, due to the uniformity of the profile. Duplicate samples for bulk density and moisture potential, and composite samples for PSA from three bays were determined.

2.2.2 NEUTRON MOISTURE METER CALIBRATION

Each soil was calibrated for neutron count ratio on θ_v (volumetric water content, %) using aluminium access tubes of internal diameter 43mm and wall thickness 3mm. A CPN 503 DR NMM was used to measure neutron counts. Each calibration point was the mean of 3 counts per depth (15 seconds each), and 3 soil ring cores used to determine each value of θ_v. Each core was located about 4 cm from the access tubes and inserted immediately after measuring the neutron count. Cores of 100 ml volume (core length 50 mm) were collected at 20 and 40 cm depths and separate calibrations completed, except for the Toolakea sand which used combined data as there was very little difference in soil physical properties at 20 and 40 cm depths. Tubes for destructive sampling were installed in a representative area of each site, spaced about 4m apart in line. Eight calibration points from saturated to drained achieved by wetting and drying, were used for all soils and depths except for the Innisfail soil at 20cm for which 7 points were used, due to high CV(%) for θ_v in one set of data which was excluded from further analysis.

2.2.3 FIELD ASSESSMENT OF DRAINAGE RATES, CUMULATIVE DRAINAGE AND STORAGE LIMITS

At each site, three bunds of diameter approximately 2m were dug and the soil was flooded in the bunds to allow saturation through the top 60 cm. The bunds at each site were separated by no more than 5 m from each other, and one aluminium access tube was inserted at the centre of each bund to a depth of 1.8m. Each bund was covered with rain out shelters, to exclude rainfall and prevent evaporation, and was located at least 5m from surface or tree vegetation. Three pairs of tensiometers were installed in each bund to record μ_s (matric potential) at 20 and 40 cm depths, using a (Soil Spec) solid state, pressure transducer to record to the nearest kPa. The tensiometers were located approximately 40 cm from the access tubes in a radial pattern. After complete wetting and cessation of infiltration, NMM readings commenced to record saturation moisture profiles down to 150 cm. Readings were taken at various intervals over the next 30 days of both the NMM and tensiometers.

Inspection of mature papaya plants growing at the research station indicated that roots extended to about 70 cm depth, with the bulk of roots in the top 40 cm of soil. Hence tensiometers were installed at 20 and 40 cm depths and the top 80 cm of each soil studied for soil water dynamics and drainage rates. Calibration equations derived for each soil were used to produce θ_v with time after saturation. For the range 0-30 cm depth, the 20 cm calibration was used and for other depths the 40 cm calibration equation was used. This soil water storage data, after averaging over three sites (bunds) within each soil type was then used to calculate cumulative drainage (the decrease in stored moisture over recorded intervals) for the 0-80 cm range, and apparent drainage rates in mm/day for the 0-80 cm range.

2.3 RESULTS

2.3.1 NEUTRON MOISTURE PROBE CALIBRATIONS

Data summarising calibration statistics for the three soils are presented as Table 2. Although limited data sets (n=8) were used for calibration, highly significant F ratios were produced attesting to the validity of the regression equations. A good range from saturated to drained moisture contents was achieved for all soil calibrations.

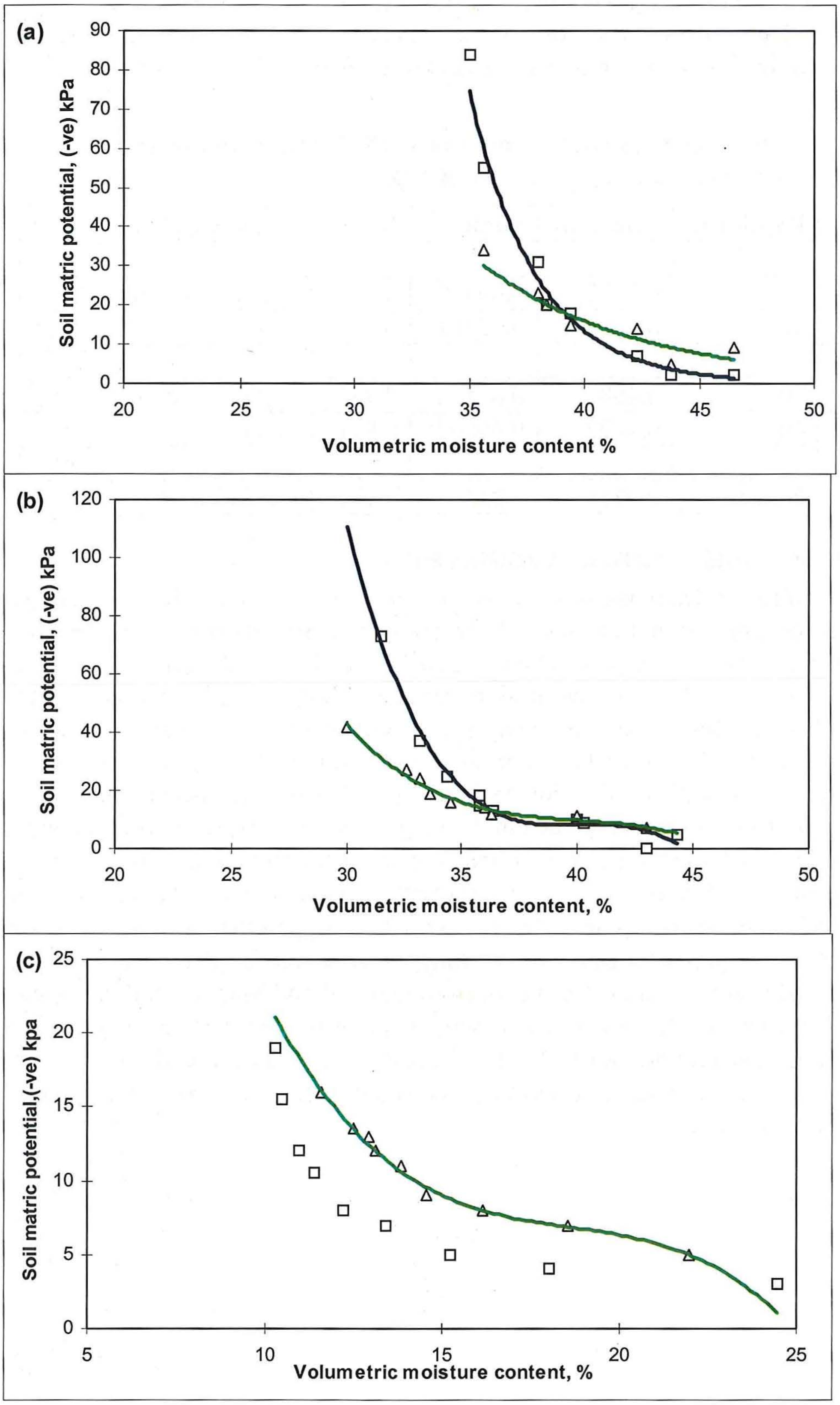
Table 2: Relationship between count ratio (NMM) and volumetric water content (%), for three soils of NQ.

Soil type	Depth cm	Intercept	Slope	R^2	F sig. Range in θ_v
Innisfail	20	0.3673	0.00732	0.954	<0.00134-50 %
	40	0.3282	0.00851	0.970	<0.001
Mundoo	20	0.4581	0.00558	0.957	<0.00127-50 %
	40	0.4477	0.00597	0.951	<0.001
Toolakea	20 + 40	0.0238	0.0243	0.976	<0.00111-24 %

2.3.2 SOIL MOISTURE POTENTIAL MEASUREMENTS

Data were collected from tensiometer studies for all soils. Initially, poor contact between the ceramic tip and the sand (Toolakea soil) especially with rapid drainage, were associated with erratic performance in such a sandy soil. A slurry of silty clay was subsequently poured into each tensiometer access hole to facilitate better contact in the beach sand. Despite this, μ_s changes after 4 days were extremely slow with a maximum of -20 kPa being reached. For the Mundoo soil, soil tensions from -5 to -73 kPa were recorded, with CV(%) for each mean of 3 sites recorded ranging up to 17.2%. The Innisfail soil was recorded in the range -2 to -83 kPa, with CV(%) ranging from 10.8% to 28% for the mean of three sites at each point. Values of μ_s for the Toolakea soil ranged from - 2 to -20 kPa with a maximum CV(%) of 8.8%.The variability of mean recorded μ_s from tensiometers does suggest that greater numbers of tensiometers are required for this type of study, however useful plots of μ_s versus θ_v were generated (Figure 2 (a), (b) and (c)). Both Innisfail and Mundoo soils indicate a more rapid change at 40 cm depth in volumetric water content as μ_s increases, although the differences are not large. The Toolakea soil was generally wetter at 40 cm depth for any value of μ_s up to -20 kPa, and shows a drainage profile that changes rapidly from 0- 10 kPa.

Figure 3: **Ranges in µs (tensiometer) versus θv (%) for (a) Innisfail soil, (b) Mundoo soil and (c) Toolakea soil at 20cm (□) and 40cm (Δ) depths. Each point is derived from 9 tensiometers located in 3 sites, and 3 NMM readings.**



2.3.3 SOIL DRAINAGE PROFILES, CUMULATIVE DRAINAGE, DRAINAGE RATES AND STORAGE LIMITS.

Changes in stored moisture over the top 80cm interval are given as Figure 4. Very good regressions were obtained (0.94-0.98) and data were fitted to hyperbolic functions of the form Y= a+ (b/(1+cx)) for each soil, and these functions were used to calculate non significant drainage rates (NSD) at 1 or 2 mm/day (Table 3).

Figure 4: **Changes in stored soil water following saturation for (a) Innisfail soil (O), (b) Mundoo soil (□) and (c) Toolakea soil (Δ).**

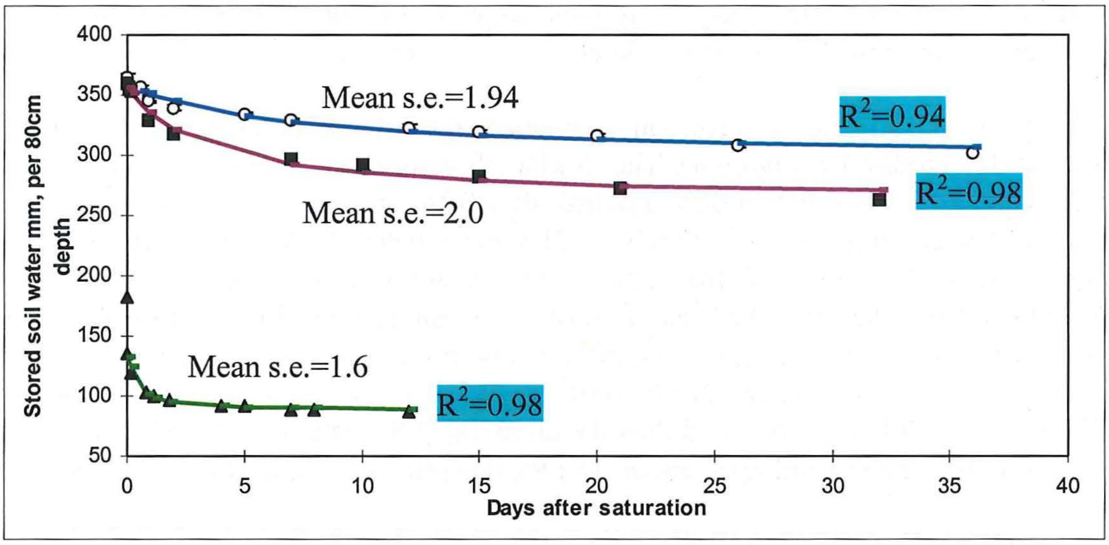


Table 3: **Calculated storage S, mm/80 cm depth, mean θv % , and time to achieve NSD rates for 1 and 2 mm/day NSD.**

NSD	Derived factors	INNISFAILtime days mm/80............ ...cm	MUNDOO time days mm/80 ....cm	TOOLAKEAti me days mm/80 ....cm
1mm/day	Storage mm per 80 cm	14.1 316	14.5 280	3.791.6
	Mean $\theta_{v\,\%}$	39.5	35	11.45
2mm/day	Storage mm per 80 cm	7.7 326	9.3 287	2.593.3
	Mean $\theta_{v\,\%}$	40.7	35.8	11.7

The Innisfail soil was the slowest draining, losing 64 mm over 30 days, compared with 97 mm for the Mundoo and the Toolakea soil 74 mm in 12 days. Average θ_v profiles based upon soil water storage (Table 3), NSD at 1 and 2 mm/day is presented as Figure 5 (a), (b) and (c) together with saturation profiles. These plots show the -5 and -10 kPa laboratory moisture retention data and tensiometer data for comparison with total stored soil water as calculated for NSD rates. The calculated NSD profiles obviously simplify the actual redistribution profiles following saturation, however in the top 60 cm saturated, the drying down profiles were quite uniform (data not presented).

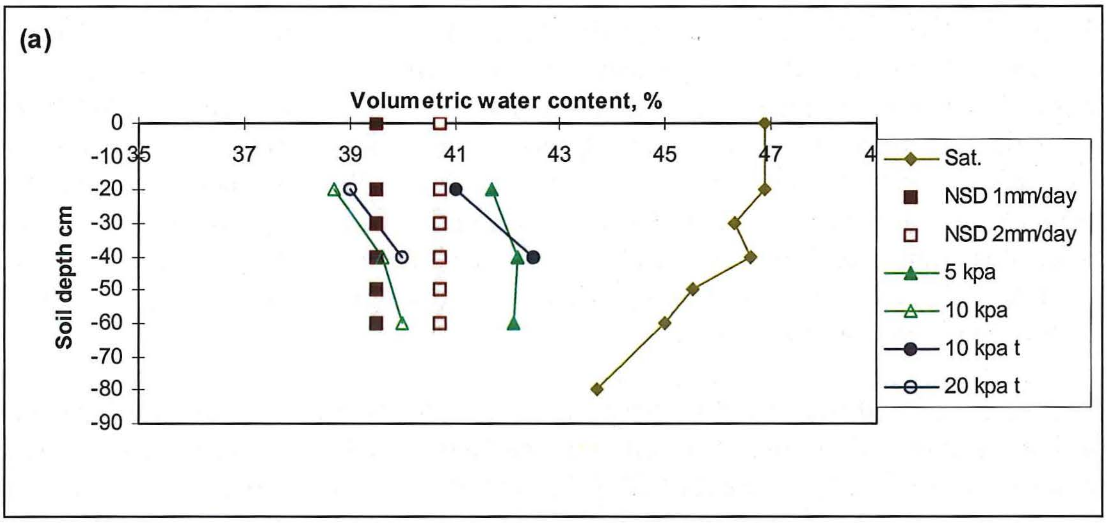
For the Innisfail soil, fastest drainage rates occurred up to day 5, after which time the drainage rate was between 1 to 2mm/day and by day 12, the drainage rate was 1.1mm/day (Figure 4 (a)). Mean calculated profile θ_v for NSD 2mm/day was closest to the tensiometer -10 kpa profile, whereas the NSD at 1mm/day lay closer to both the 20 kPa tensiometer profile and the laboratory -10 kPa profile. From Figure 5 (a), change in θ_v is most rapid up to about -20 kPa. The moisture profiles from laboratory extractions were drier than those indicated by field tensiometers. Both profiles for NSD generally lie inside the extraction profiles, so either level of NSD could be chosen. For NSD at 1mm/day, S is equivalent to 158 mm/40 cm, and for NSD 2mm/day, S is about 163 mm/40cm depth, which is quite close.

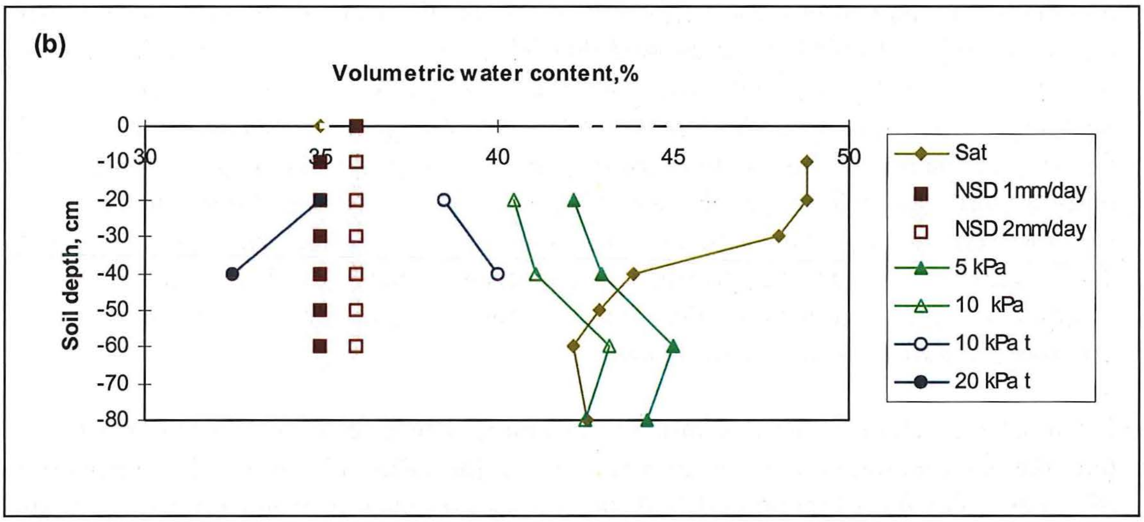
The Mundoo soil after 2 days had a drainage rate of 10.7mm/day, decreasing to 1.4mm/day by day 10 (Figure 4). The -5 kPa laboratory retention data (Figure 5 (b)) was close to the moisture profile attained after 0.14 days, and with a high drainage rate, soil at this time was still very wet. The tensiometer -10 kPa moisture retention was close to that obtained from the laboratory study at -10kPa, and the -20kPa tensiometer data lay near the 7 day θ_v profile. Mean calculated θ_v profiles (Figure 5 (b)) for two NSD values, show similarity, and both are much drier than all extraction data except the tensiometer -20 kPa profiles. The NSD of 1mm/day is probably too close to the -20 kPa profile, and thus the 2mm/day NSD rate is preferred, given that change in θ_v is most rapid up to about -15 kPa, declining thereafter (Figure 3 (b)).

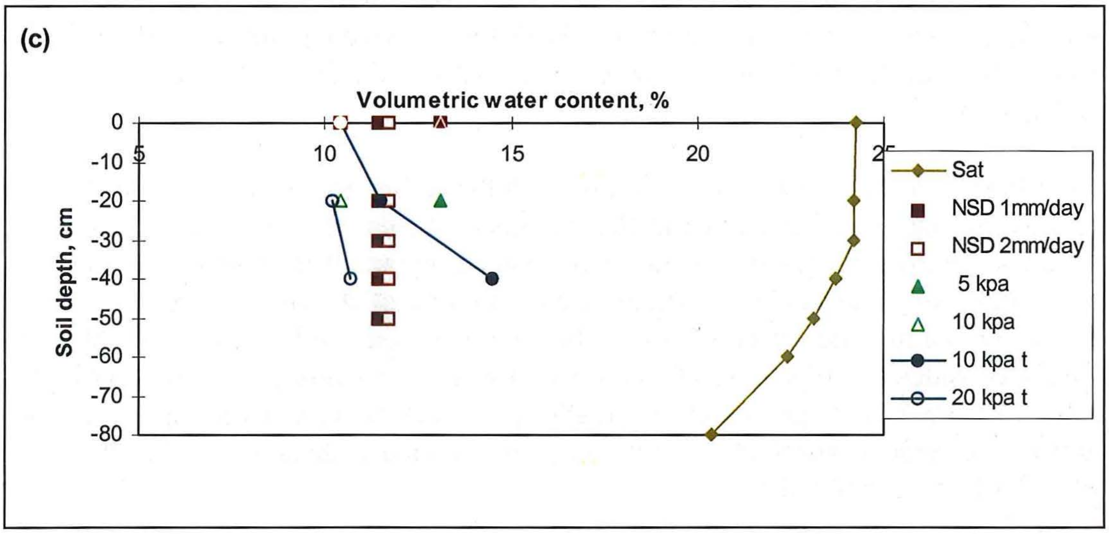
The decline in θ_v(Figure 5 (c)) for the Toolakea soil was rapid at all depths until day 4, at which time, apparent drainage rate was 1.9 mm/day. The NSD moisture profiles are essentially identical and both are closest to the -10 kPa tensiometer profile, The decrease in soil θ_v with μ_s begins to slow appreciably near -8 kPa (Figure 3(c)) thus the NSD rates are not likely to be associated with wet soils.

Photograph 1: Flooded bund at SJRS site, showing tensiometers and NMM tube.

Figure 5: Changes in θv (%) from saturation for different μs and NSD, for (a) Innisfail, (b) Mundoo soil, and (c) Toolakea beach sand. Data refer to the soil depth range 0 to 80cm, and kPa refers to matric potential recorded by tensiometers.







2.4 DISCUSSION

Childs (1969) states that for profile drainage rates of a few mm/day, water potentials may vary from as high as -0.5kPa for a highly stratified soil to as low as -60kPa in deep dry land soils, and that the use of a single moisture potential such as -33kPa to define field capacity, has the potential to create huge errors in water retention estimates. This is related to the flat nature of most soil moisture retention curves at the wet end, where large changes in water content are often associated with small changes in moisture potential. This author elaborates upon the difficulty of defining a "universal" NSD and concludes that statements such as "field capacity for 2mm/day drainage" are appropriate. The reduced drainage of Innisfail series soils is suggested from this study, and it continues to drain slowly for a long period of time. Contrastingly, the high permeability noted for other Krasnozems (Bridge and Bell 1994) is verified from the current study.

The NSD rate and associated θ_v represents the integration of all factors influencing soil water movement through the soil, thus can be regarded as the true indicator of soil water upper storage level. Reid *et al.,* (1984) used 1 mm/day as the NSD, but Childs (1969) stated that a unique point in time associated with NSD does not always occur, and that some indication must be given of what constitutes negligible drainage. Other authors (Gardner 1988) have suggested that NSD was best arrived at by allowing for plant uptake of water above the NSD and measurement of μ_s above and below the θ_v associated with NSD. In this study, soil water storage for NSD at either 1 or 2 mm/day was shown to be identical for the Toolakea soil. For the Mundoo soil, a rate of 2 mm/day was preferred, as this value lay between the –10 and –20 kPa tensiometer moisture retentions. For the Innisfail soil a rate of 1mm/day seemed appropriate for a similar reason. It is important to consider the various NSD rates not only in relation to evaporation rates but also to the shape of the moisture drainage curve and the proximity of soil moisture retention data.

For three soils studied, the tensiometer -33 kPa moisture retentions were much lower than the NSD storage retentions thus ruling out this value of μ_s to set the upper limit of storage. For the Mundoo soil both laboratory estimates of water retention greatly exceed water retention at NSD or "field capacity". Working with Figrue 2 (b) and the moisture content of 36%, the derived μ_s for the USL is about -15 kPa. For the Innisfail soil, with a moisture content of 39.5% at NSD, the equivalent μ_s for the USL is about -18 kPa, and for the sand with 11.5%, μ_s for the USL is about -8 to -15 kPa. (Figure 3 (a, b and c)).

The Mundoo soil response is more in line with the earlier comments of Childs (1969), concerning flat retention curves at the wet end, whereas the Innisfail soil does not appear to follow this general trend. Inspection of Figures 3 (a) and (b) clarifies this point, indicating the steeper moisture retention curve of the Innisfail soil. However, the -1500 kPa moisture retention of the Innisfail soil is much lower than the Mundoo with a considerably higher AWC as a consequence. The higher clay content of the Mundoo (Table 1) suggests that the smaller pore neck size results in higher suctions required to remove water at the dry end of the moisture characteristic, than for the silty clay texture Innisfail soil.

Aids in irrigation management and soil water monitoring for the three NQ soils have been established in this study. For any desired rooting range, the parameters can be changed. For the Toolakea soil, the range in μ_s at full point is -8 to -15 kPa, and given that the 20 cm layer drains rapidly over this level, the lower value of -8 kPa is appropriate. The Mundoo and Innisfail series soils both have similar full point μ_s `s in the range of -15 to -20 kPa.

2.5 CONCLUSIONS

Tensiometer μ_s particularly in the -10 to -20 kPa, range recorded in conjunction with derived non significant drainage rates of 1 to 2 mm/day, were found to be useful in setting upper storage limits for soil water management. Laboratory measurements of μ_s at -5 kPa overestimated USL, and at -10 kPa over or under estimated USL. Drainage of the Innisfail soil was comparatively slow, the Mundoo soil fast, and the sand rapid. Tensiometer μ_s at -33 kPa was always an underestimate of the USL. For the Toolakea soil full point was found to be at -8 kPa and 11.8% volumetric water content; the Mundoo soil at -15 to -20 kPa and 36%; and the Innisfail soil at -15 to -20 kPa and 39.5% volumetric water content.

CHAPTER 3: ESTABLISHING REFILL POINTS FOR IRRIGATION MANAGEMENT OF THREE COMMONLY USED SOILS FOR PAPAYA PRODUCTION

3.1 INTRODUCTION

Historically, the determination of available water capacity (AWC) has been determined in the laboratory, using pressure plate apparatus and core samples. The AWC is that either between -10 kPa or -33 kPa, and the permanent wilting point (PWP) of -1500 kPa. Several authors have found this approach to be often inaccurate, overstating the actual AWC for plants (PAWC) and not considering drainage issues (Gardner *et al.* 1981, Reid *et al.* 1984, Robinson and Power 1986). Efficient soil water management requires detailed knowledge of the soil, plant and irrigation systems and the minimising of drainage and leaching losses. In North Queensland, the Papaya industry commonly enjoys several luxuries such as several undeclared groundwater shires, plentiful supply of free, good quality water from rivers and bores and a high annual rainfall (>3000mm). Against this is a rapidly rising water demand. The water supply is not unlimited, and needs to be conserved and efficiently utilised now, to improve quality and yield of farm produce, and to minimise the risk of water shortages and contamination of ground waters. As outlined in Chapter 1, the level of irrigation management in North Queensland is not high, and efforts to improve this are not well supported.

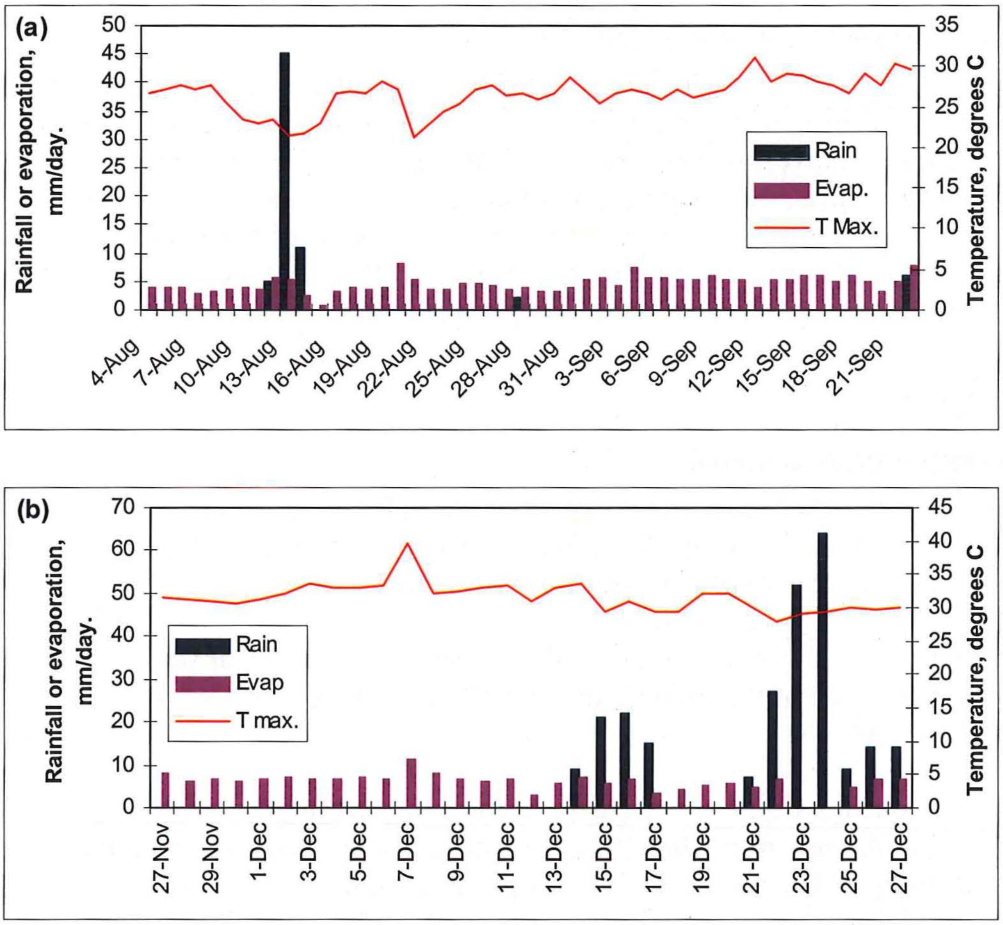
Chapter 2 looked at the issues associated with defining the upper storage limit, commonly referred to as the full point. This chapter goes on to examine papaya responses to applied water stress and definition of the lower storage limit, or refill point and PAWC for three soils commonly used for papaya production in North Queensland. Leaf water potential and relative water content data were collected but results were not reliable. The presence of sap filled tissues in papaya leaves and petioles is thought to be the reason for this.

3.2 MATERIALS AND METHODS

3.2.1 TIME AND LOCATION OF EXPERIMENTS

The soil types chosen for this study were the Mundoo series Krasnozem from South Johnstone Research Station (SJRS) and the Toolakea series beach sand from Etty Bay, as detailed in the preceding paper. Trees were not available to study for the Innisfail series alluvial soil at SJRS. Data were collected from the Mundoo soil in August and December 1996, and for the Toolakea sand in December 1996. Hybrid 1B plants planted in November 1995 were used, in single lines at 1.5 m spacings and 4m row spacings at SJRS. For Etty Bay, mixed hybrids planted in double lines in November 1995 spaced at 2m x 1.8m , with a row spacing of 6m were used. Climatic data for SJRS during the experiments (Figure 6 (a),(b)) are relevant to the Toolakea soil site as well.

Figure 6: **Daily rainfall mm , evaporation mm and maximum temperature0 C for South Johnstone Research Station in (a) August/ September 1996 and (b) November/December 1996.**



3.2.2 SOIL WATER MEASUREMENTS

A minimum of three aluminium access tubes were installed at each site for measurement of volumetric soil water content (θ_v) as described previously. Tubes in both watered and unwatered plots were located 25 cm from plants, between sprinklers and plants. Measurements of θ_v were determined using count data from CPN 503 Neutron Moisture Meter (NMM) at 20, 30, 40, 50, 60, 70 and 80 cm depths and the calibration equations previously developed. Values of θ_v were used to calculate stored soil moisture for 0-40cm and 40-80cm depths ranges and means calculated. At the commencement of each experiment at each site soils were wet up to at least 50 cm depth to ensure complete root zone moisture availability. Initially, papaya rooting depth was set at 40 cm as previous excavations had revealed most papaya roots (mature trees) located in the top 40 cm zone of soil. At each site plants were split into 2 groups (lines) of 10 plants each; those which were irrigated to maintain a wet profile and those which were not watered viz. stressed by closing off sprinklers. It was not practical to use rain out shelters. Watered plants were irrigated by replacing water lost over the range 100 to 50 % depletion of ASW.

Tensiometers were installed at 20 and 40 cm depths at the same plants used for NMM recording, with at least 4 pairs per treatment. Soil matric potential was measured using a solid state pressure transducer (Soil Spec system) and means of at least 4 tensiometers per site and depth calculated. At Etty Bay, previous experience had shown that tensiometers installed directly into the sand tended to lose contact between the ceramic tip and sand as drying occurred, so a slurry of silty clay soil (<2mm sieved) was poured into the base of each hole drilled for tensiometer installation.

3.2.3 Fruit and flower measurements

In August 1996, 10 plants each were selected for watered and stressed treatments at SJRS, and the position of the most recently fertilised ovary recorded on each plant. The length and diameter of these marked fruits on each of 10 trees was measured regularly using calipers. The total number of all fruits and flowers above this position were subsequently recorded for each plant for the duration of the experiment until September 1996. For subsequent experiments at SJRS and at Etty bay, only fruit growth data were collected, utilising 10 fruit per treatment.

3.3 Results

3.3.1 Reproductive growth

Summarised fruit growth data and derived volumes (Table 4) showed rapid changes with time. Fruit volume was calculated from measured fruit diameter D, and length L, and the formula for volume of a prolate spheroid, where

$$\text{volume} = 4.19\ D^2\ L$$

The data indicated uniform responses at all sites such that as days of stress increased, the volume expansion of the fruits from stressed trees declined relative to fruits from watered trees (Table 4).

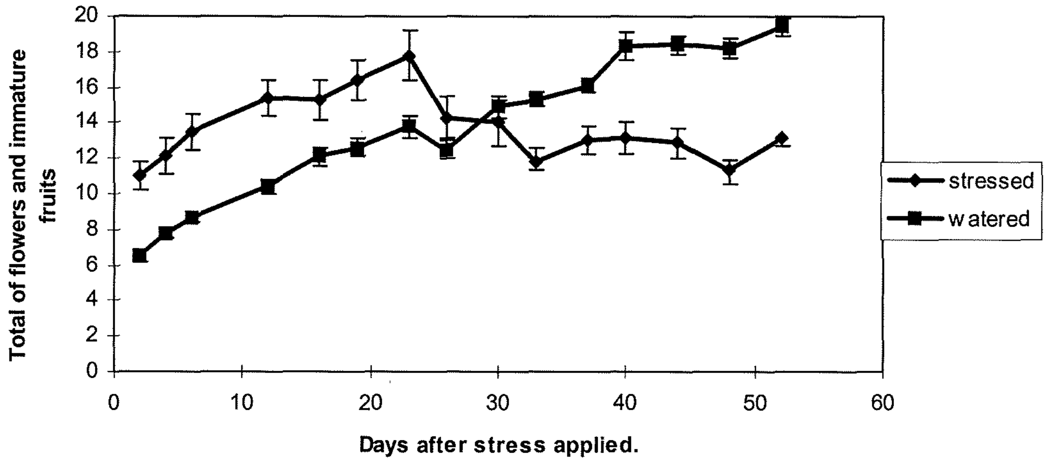
In Table 4, non-significant fruit size differences are highlighted by an *. In the Mundoo soil in August, from after 19 days of stress (although heavy rain fell at 10 to 12 days of drought) the fruit from stressed plants declines relative to the fruit from watered plants. The estimated period for drought to effect fruit size is then 7 days, using the last rainfall at day 12.Figure 7 shows this at about day 22 as a decline in total number of flowers and immature fruit recorded from droughted trees, which continues on to day 48. For the same soil in November it took 6 days to notice a significant decline in relative fruit volume from 91% to 63 % at day 15. This is a true test as no rain fell in the period 1 to 21 days of drought.

For the Toolakea soil, from day 3 on, the fruit from droughted plants declined relative to that from watered plants, although significant differences were not noted until day 12. This is shown as a decline in relative fruit volume to below 100% at day 9. By day 5 there was no significant difference in fruit volumes, suggesting that the fruit from watered trees was catching up and beginning to overtake, fruit size of the droughted plants. It might be possible to interpret this as the onset of water stress in the droughted plants.

Table 4: Papaya immature, fruit volumes at different times and sites.

Mundoo-November														
Days of drought	2	3	6	8	10	13	15	17	20	24	30			
Fruit vol (cm^3) watered	28.3	37	46.9	63.4	76.3	94.4	115.1	136.7	155.7	196.4	274			
Fruit vol (cm^3) stressed	24.2	32.2	42.7	53	60	63.5	72.6	90.9	111.5	151.7	201			
Relative fruit volume %	85	87	91	84	78	67	63	66	72	77	73			
$T_{obs.}$ 5%	3.63	3.53	2.67	5.51	7.46	12.26	14.77	14.73	11.85	10.98	16.15			
Mundoo August														
Days of drought	2	4	6	12	16	19	23	26	30	33	37	40	44	48
Fruit vol (cm^3) watered	15.8	24.3	30.3	65	81.3	91.5	117.5	136.3	185.4	198.5	221	280	322	397
Fruit vol (cm^3) stressed	19.3	24.1	32.3	66	87.9	98.3	114.1	111.8	147.7	143.5	174.6	216	243	287
Relative fruit volume %	122	99.5	107	102	108	107	97	82	80	72	79	77	75	72
$T_{obs.}$ 5%	2.89	0.08*	1.21*	0.46*	2.82	2.47	1.15	7.8	10.5	14.2	11.6	14.3	16.8	21.4
Toolakea December														
Days of drought	1	3	5	8	10	12	15	18						
Fruit vol (cm^3) watered	11.8	16.6	24.2	32.4	38.8	47.2	59.8	76.1						
Fruit vol (cm^3) stressed	16.8	22.4	26.9	34	37.3	40.8	54.2	69.7						
Relative fruit volume %	143	135	111	105	96	86	91	92						
$T_{obs.}$ 5%	6.4	5.1	2.06*	1.05*	0.9*	3.1	2.05	2						

Figure 7: **Total number of immature fruits and flowers (per plant) in August at SJRS for watered and water stressed papaya plants. Bars indicate s.e. values.**



3.3.2 SOIL WATER DYNAMICS AND FRUIT VOLUME RESPONSES

Large differences in stored soil water S, of the watered and unwatered papaya plants at both sites were obtained (Figs. 8 (a),(b) and (c)). Very low values of S were attained at SJRS after 7 days of drought in December (Fig.8 (a)) and after 22 days in September , although rain fell earlier (Fig. 8(b)). These S values reached well below the PWP lower storage limit implying water stress, although certain factors in relation to this will be discussed later. Air temperatures and evaporation rates were higher in December (Figs. 6(a),(b)) and water depletion occurred more rapidly in December than in September.

Data of S dynamics for Toolakea soil (Fig. 8(c)) indicated the extremely limited water holding and release capacity of sands. The minimum recorded S after 10 days of stress was 80 mm, the maximum 110 mm at commencement, and both values were much higher than the PWP lower storage limit of 20 mm.

The net change in stored soil water (Figs 9, 10(a),(b),(c)) shows for all sites that the unirrigated plots declined rapidly in storage change (ie plant water use plus drainage) whereas the irrigated plots continued with high changes, usually net losses. The 40-80 cm zone of irrigated plots at SJRS had regular storage gains ie drainage from the upper, 40 cm zone. For watered plants, net losses in the top 40 cm were consistently much higher than net losses in the 40-80 cm zone, suggesting that both drainage and plant water usage were higher in the top 40 cm zone. In contrast, unwatered plants showed similar rates of net loss in both zones, particularly as days of drought increased. The unwatered plants showed much smaller changes in stored water than did the irrigated plants.

In the Mundoo soil, in August at day 19 (stress point from Table 4, relative fruit volumes), S was recorded as 210 mm per 80 cm depth (Fig.8(b)), and in November S was 190 mm at day 6 (Fig.8 (a)). For the Toolakea sand, stress appears from day 5 onwards, at which time S (Fig 8(c)) is 86 mm per 80 cm depth.

Figure 8: Changes in total soil water S mm (0-80cm), for watered plants (filled boxes) and unwatered plants following drought in (a) Mundoo soil December (b) Mundoo soil August, and (c) Toolakea soil December 1996. Bars indicate s.e. values, and upper and lower lines indicate respectively upper storage limit and PWP.

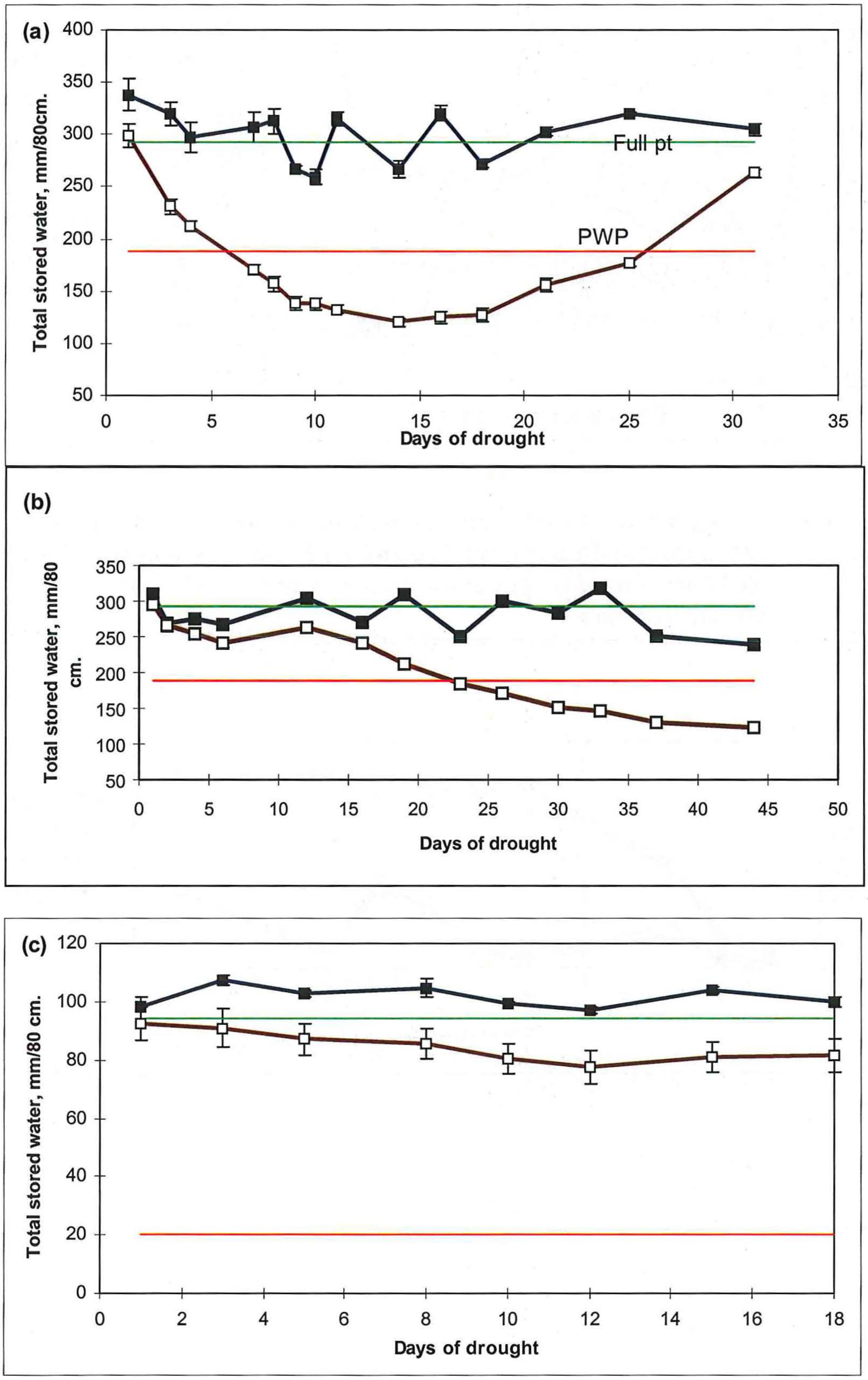


Figure 9: **Changes in stored soil moisture S, in relation to applied irrigation and days after wetting up, for the Mundoo soil in August.**

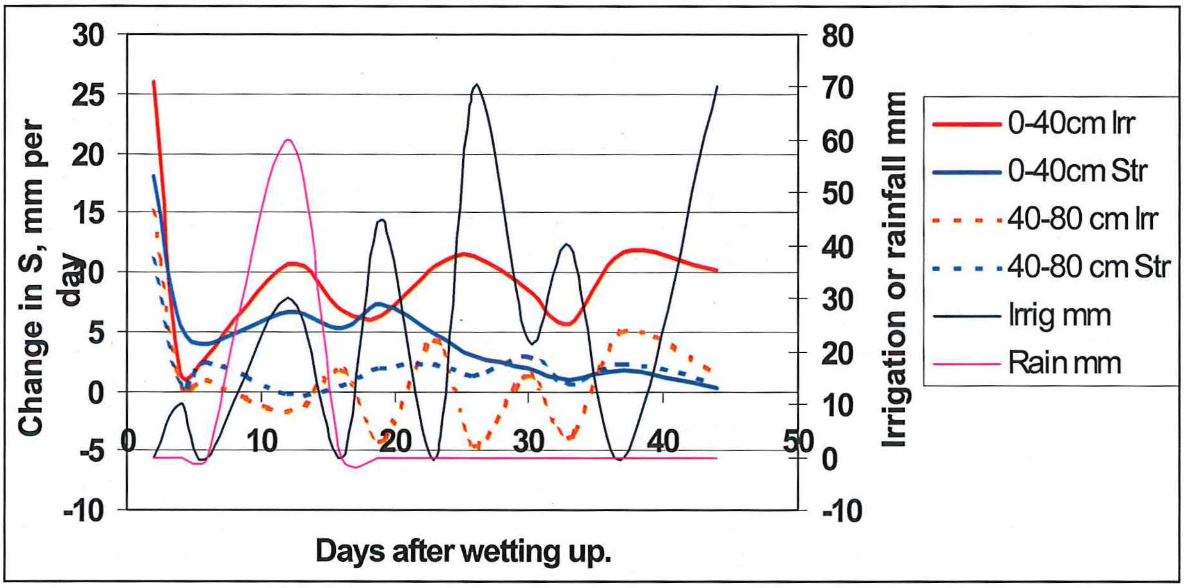
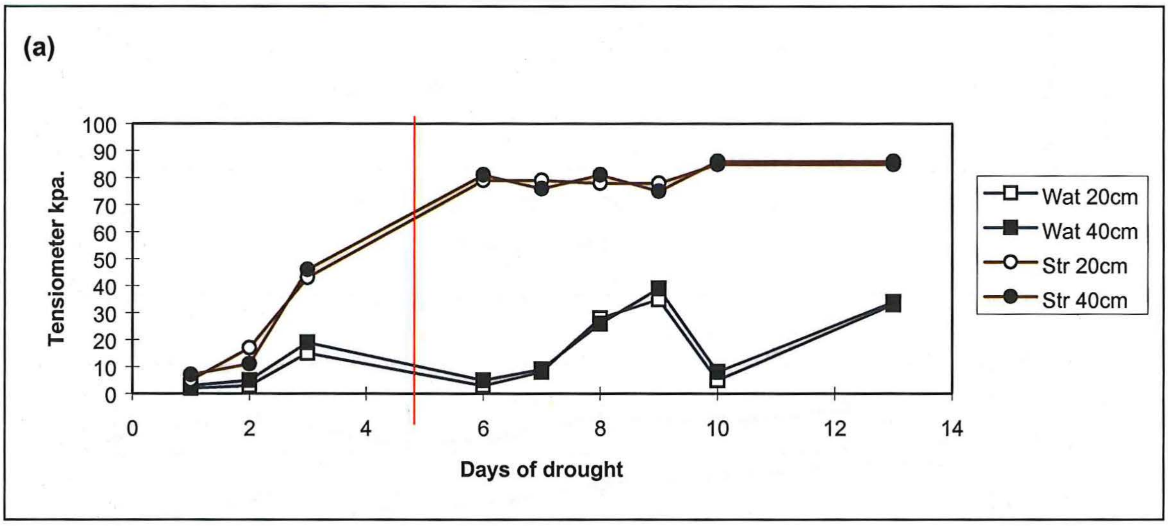
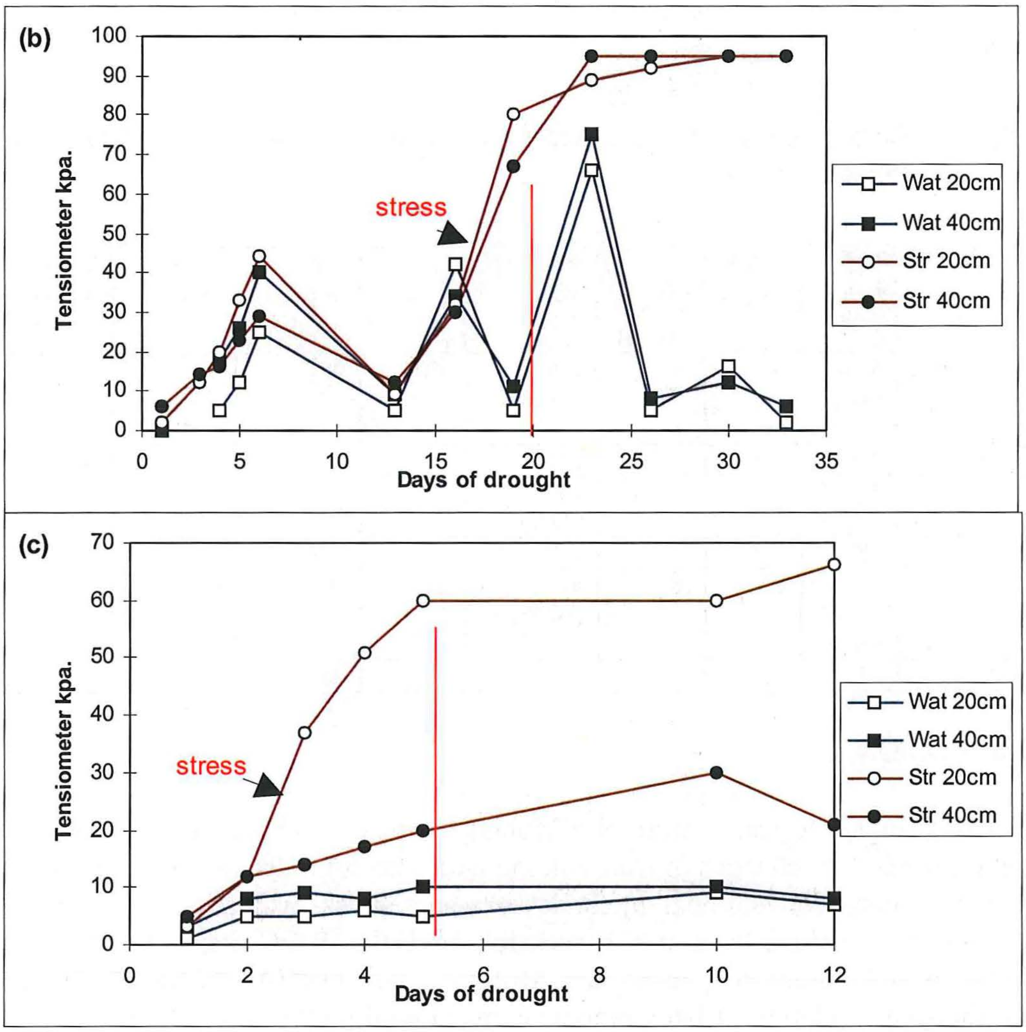


Figure 10: **Changes in soil matric potential with days of drought for Mundoo soil in (a) Nov/Dec, (b) Aug/Sep and (c) Toolakea soil in Dec 1996. Red lines show days of significant fruit volume decline in unirrigated plants.**





Changes in μ_s with days after stress applied highlight the rapid rise in unwatered plots, to levels much higher than the watered plots (Figures 10 (a), (b) and (c)). For the Mundoo soil in November (Figures 10 (a)), the range over which stress commenced was -40 to -80 kPa, whereas in August (Figure 10 (b)) it was -30 to -80 kPa, established by referral to Figure 10 (a) and (b) and associated changes in fruit volume (Table 4). For the Mundoo soil, a mean critical μ_s value could be set at -60 kPa. For the Toolakea soil, after day 5 μ_s was –60 kPa at 20 cm and –20 kPa at 40 cm depth. Referring to Figure 3 (c) in Chapter 2, at moisture potentials lower than –20 kPa, moisture content changes very slowly below 10%; viz the soil is well drained and likely to allow restricted water uptake. This is observed from Figure 8 (c) where mean water content of 10% (80 mm/80cm) was the lowest level attained in unwatered plants.

The refill point for both soils can be estimated by averaging S values associated with fruit stress, and calculated S values from the moisture characteristics, using μ_s values recorded with fruit stress onset (Table 4). The refill S for Mundoo was thus averaged at 217mm /80 cm depth using both August and November data sets. For the Toolakea sand, the S refill was averaged at 83 mm/80 cm depth.

The results from this study are summarised as Table 5, setting out the full points (as derived from Chapter 2) and the refill points and associated matric potentials. From these values PAWC is derived, and compared with AWC (between –10 kPa and –1500 kPa).

Table 5: Derivation of PAWC based upon different lower storage limits, for three soil types.

Soil	Full pt mm	PWP mm	μ_s kPa full pt	Refill pt. Mm	μ_s kPa	AWC , mm	PAWC mm	PAWC, % depletion of AWC
Innisfail0-40 cm	158 (39.5 %)	63	-18	110 (27.5%)	-60	95	48	
0-80 cm	316	127		221		190	96	50
Mundoo 0-40 cm	144(36.0%)	89	-15	108 (27%)	-60	74	36	
0-80 cm	288	185		217		148	71	48
Toolakea 0-40 cm	47 (11.8 %)	8	-8	41 (10.3%)	-20	39	6	
0-80 cm	94	16		83		78	11	14

3.4 Discussion

Papaya plants subject to water stress in a Mundoo clay soil and a Toolakea sand soil both demonstrated that changes in fruit volume was a useful indicator of water stress. However, the more conventional methods of water stress evaluation such as the pressure bomb technique was not successful, and the RWC inconsistent. This observation is not unique to papaya and Milburn *et al.* (1990) concluded that for bananas, the free exudation of latex renders conventional methods for studying water potential impractical or suspect, and in cashew and mango difficulties arise in differentiating sap and xylem fluids.

The use of fruit growth data to determine irrigation scheduling has had a confused history to date, but Zahner (1968) concluded for horticultural species "the rate of enlargement by fleshy fruits is strongly reduced following the rapid depletion of soil moisture". Barrs (1968) concluded that despite considerable research into the relationships of fruit size and water availability, only qualitative cases exist. Some data of relative fruit volume and stored soil water were however obtained in this study for papaya, and show clear differences of fruit volume from watered and droughted plants, as S declines. Masri *et al.*(1990) found in papaya in Malaysia that after 12 to 16 days of drought , fruit circumference was significantly lower in unwatered plants, and that μ_s was declining below -50 kPa . Critical μ_s values for the Mundoo and Toolakea soils were respectively -60kPa and -20 kPa , for the current study.

In Israel in sand soil, Bravdo *et al.* (1992) found that apple yields were reduced significantly at matric potentials higher than -15 kPa, for drip irrigated trees on sands. Robinson (1996) and Robinson and Bower (1987) found that above -40 and -20 kPa respectively, banana yield and physiological functioning declined. These authors also stated that the allowable depletion of AWC ranged from 10 to 33%. Bananas and papaya have similar growth requirements and locations thus the comparative data are of interest, and are lower in μ_s than in the papaya study, for Mundoo soil type.

The S value associated with PWP for the sand is well below the lowest S values measured in the field and that associated with RFV 100%. In contrast to the Mundoo soil in which plants were able to extract water below PWP, the sand does not apparently allow this presumably due to the extremely low hydraulic conductivity's of soil water movement in dry sands. The Mundoo soil recorded extremely low θ_v 's as the soil dried, well below PWP, and this raises some doubts about the usage of NMM in dry soils. As soils dry, neutron scattering increases and the sphere of importance increases typically from 15 cm in wet soils to about 50 cm in very dry soils (Gardner *et al.* 1996). This has consequences particularly for the measurement of soil water in the upper 40cm, at low θ_v as the chances of neutron "loss" increase, and recorded θ_v 's may be artificially low. The data for the Mundoo soil (upper 40 cm) below PWP are not totally reliable therefore, and for the Toolakea sand, the issue does not arise due to the very limited range of S values available for plant water uptake, all well above PWP.

Stegman (1983) presented a generalised curve relating relative growth/yield and allowable water depletion, such that >50% depletion of AWC was associated with declining plant performances. This leads to the concept of plant available water capacity PAWC and effective rooting zone depths. Table 5 gives compares results of PAWC based upon the refill point and full point, and the AWC derived from the -10 kPa and -1500 kPa moisture retention's.For the Toolakea soil use of AWC grossly exaggerates PAWC, as does even the use of 50% depletion setting. Only the LSL provides a realistic estimate of PAWC , equal to 14% allowable depletion of AWC and 0.0137mm /mm soil. For the Mundoo soil, PWP also is too high in estimating the lower storage limit, but PAWC is 48% of AWC thus close to the 50% depletion point. The PAWC is 0.088 mm/ mm soil. For both soils, PAWC based upon -10 kPa and -1500 kPa laboratory measurements grossly exaggerates water availability. For the Innisfail soil the refill point was estimated on the basis of 50% depletion of AWC, giving a value of 0.12 mm/ mm soil, which is 9 times the capacity of the sand (Toolakea).

The need to, and problems encountered , in clearly defining rooting depth and thus PAWC, was also raised as in issue in this study. Data from Figure 9 indicate that the change in S in the upper 40 cm zone was generally greater than that in the lower 40 cm zone. This suggests that plant water use and drainage loss combined is greater in the upper zone, with a greater mass of roots. However, the importance of the lower zone for moisture uptake is apparent during stress periods.

3.5 Conclusions

Conventional methods for determining plant water status of papaya plants were not successful in this study due either to equipment unreliability or uncertainty relating to plant responses to applied methods. However, the determination of derived relative fruit volumes from stressed and watered plants did prove to be a useful indicator of plant water stress, such that when stored soil moisture declined below the lower storage limit, fruit volume from droughted plants decreased rapidly.

The lower storage limits were derived by considering soil matric potential changes and changes in fruit volumes, in relation to decreasing soil water contents, which gave

PAWC much lower than the calculated AWC for both soils. PAWC based upon 50% depletion of AWC overestimated PAWC for the Toolakea sand, and gave similar PAWC for the Mundoo clay, in comparison with refill point derived PAWC. The Mundoo PAWC was calculated at 0.088 mm water/ mm soil, for the Toolakea soil was 0.0137mm /mm soil. For the Innisfail series soil, total reliance upon the 50% depletion was required due to lack of plant response data, and PAWC was set at 0.125 mm water/ mm soil. PAWC based upon laboratory retention data at -10 kPa and PWP grossly exaggerated PAWC for both soils and highlights the limitations of such laboratory determinations.

CHAPTER 4: STUDY OF EMITTER AND SPRINKLER WETTING PATTERNS, FLOW RATES AND PRECIPITATION RATES.

4.1 INTRODUCTION

In the Irrigation Trial (Chapter 5) several different irrigation emitters and sprinklers were evaluated for papaya production and water usage. In order to evaluate these systems fully, some understanding of the rate of water entry into the soil, the rate and extent of downwards flow and lateral flow needs to be achieved. This is important in relation to irrigation scheduling to know the gross precipitation rates of different systems, the area wet with time and the temporal variation of the wetting front. It is also important in relation to irrigation design on different soil types, as the soil vertical and horizontal hydraulic conductivity's will determine the range of suitable irrigation systems that can be used efficiently.

Direction of flow, prevailing soil water content, conductivity and rate of infiltration into the soil complicate the study of water movement. The distance radially, from the emitting source or the outlet, of the wetting front and the change in soil water content following redistribution, are essentially the two properties to assess in such a study. Tensiometers (Soil Spec system) were used to monitor wetting front changes and Neutron Probe readings taken to follow soil water content changes. The delay of tensiometers in responding to soil moisture potential changes was also assessed in this study.

4.2 METHODS AND MATERIALS

In the first study, the variation in infiltration and wetting front movements, three types of outlets were selected in conjunction with the Mundoo soil site, in June 1996. Systems studied were: single dripper, single drip tape, and single sprinkler. The characteristics of each system is described in Chapter 5. It was not possible to find undisturbed, unplanted areas in the irrigation trial block, consequently sites with trees actively growing were selected. Obviously this will produce different results from a block without root system and plant uptake effects, but given the duration of the study (3 hours) water uptake would be relatively small in comparison to that applied.

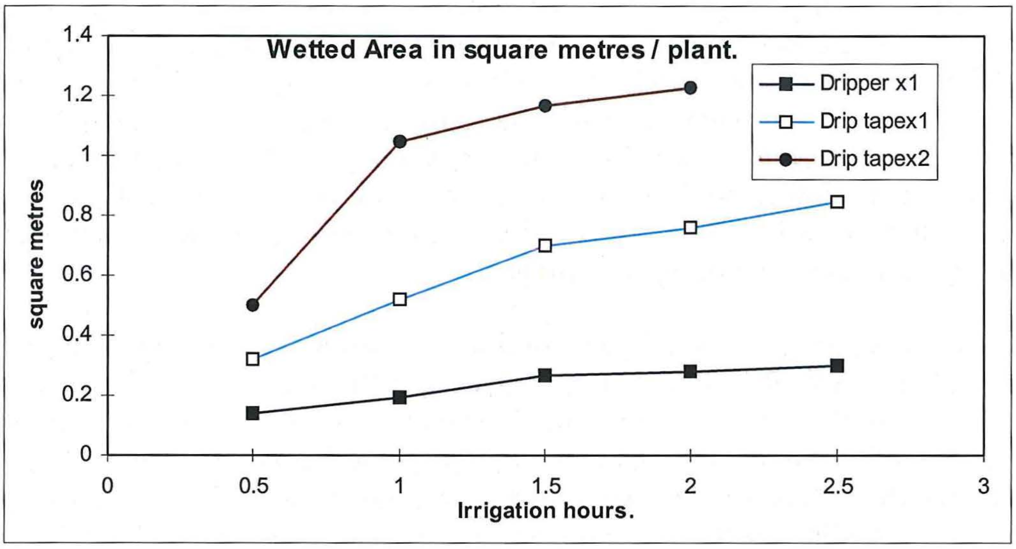
The second study study was conducted in July 1997, in the Irrigation Trial Plots. Tensiometers were located at various distances and orientations from outlets at 10, 20, 30 40 and 50 cm depths. The actual orientation and distance of tensiometers from the outlet is indicated on each figure in Figures 12, 13, 14 and 15. Neutron probe tubes (previously installed) were not measuring in exactly the same wetted area, but a similar area.

Readings of tensiometers and probe sites were taken every 30 minutes, from the commencement of irrigation. Irrigation duration varied from 2 to 2.5 hours as indicated on each figure. The soil was quite wet before irrigation due to heavy recent rains.

4.3 RESULTS AND DISCUSSION

The increase in wetted area for emitters leveled off at about 1.5 hours of irrigation, at which time wetted areas per plant were 1.2 m^2, 0.7 m^2 and 0.2 m^2, for respectively double drip tape, single drip tape and single drippers (Figure 10). In this soil type, it takes about 1.5 hours for wetted circles from individual drippers (35 cm spacing) of drip tape to join up, to form a continuous column. After 1 hour of irrigation, wetted area is about twice that achieved after 30 minutes. For single button drippers (8L/hr) there is not a great deal of variation of wetted area with time.

Figure 11: The variation in wetted area per plant with time for three emitters.



Knowledge of how fast water enters the soil and moves through it beyond the root zone is essential for irrigation management decision making. The gross precipitation rate of the outlet (Litres per hour/ wetted area) has to be matched to soil infiltration rates, and the storage capacity of the soil over root zone layers of differing physical properties. This is an extremely complex 3 dimensional soil physics problem, for which field studies on different soil types can be used to provide empirical solutions. From Figure 12 (c) the rapid wetting front advance through the root zone (0-40cm) is apparent with an 8L/hr button dripper. Some time after about 30 minutes of irrigation, the soil is close to, or exceeding full point. The sub root zone was very wet prior to irrigating and this indicates over watering in previous irrigation cycle or the lack of root activity below 40 cm depth. Maximum irrigation run time was set at 30 minutes. Single line drip-tape (Figure 12 (b), 30 cm spacing, 2.5L/hr) illustrates a totally different wetting pattern of the soil before and during irrigation. To wet the root zone to near full point took 2 hours, at which stage the subsoil at 50 cm was at full point. The wetting front had a mean rate of advance of about 25cm/hour. To allow for redistribution and to avoid subsoil drainage, the recommended maximum run time was set at 1.5 hours.

Micro-sprinklers (40 L/hr, Figure 12 (a)) showed the slowest rate of wetting of all three outlets. After 2 hours of irrigation, there was only slight increases in moisture content at 40 cm depth and the mean rate of advance was about 25cm over 2 hours or 10 cm/hr. To allow for redistribution and to minimize drainage, the maximum run time for this soil could be safely set at 3 hours.

Figure 12: **Changes in volumetric water content (%) with time after irrigation commenced for (a) micro-sprinkler (b) single drip-tape and (c) single dripper.**

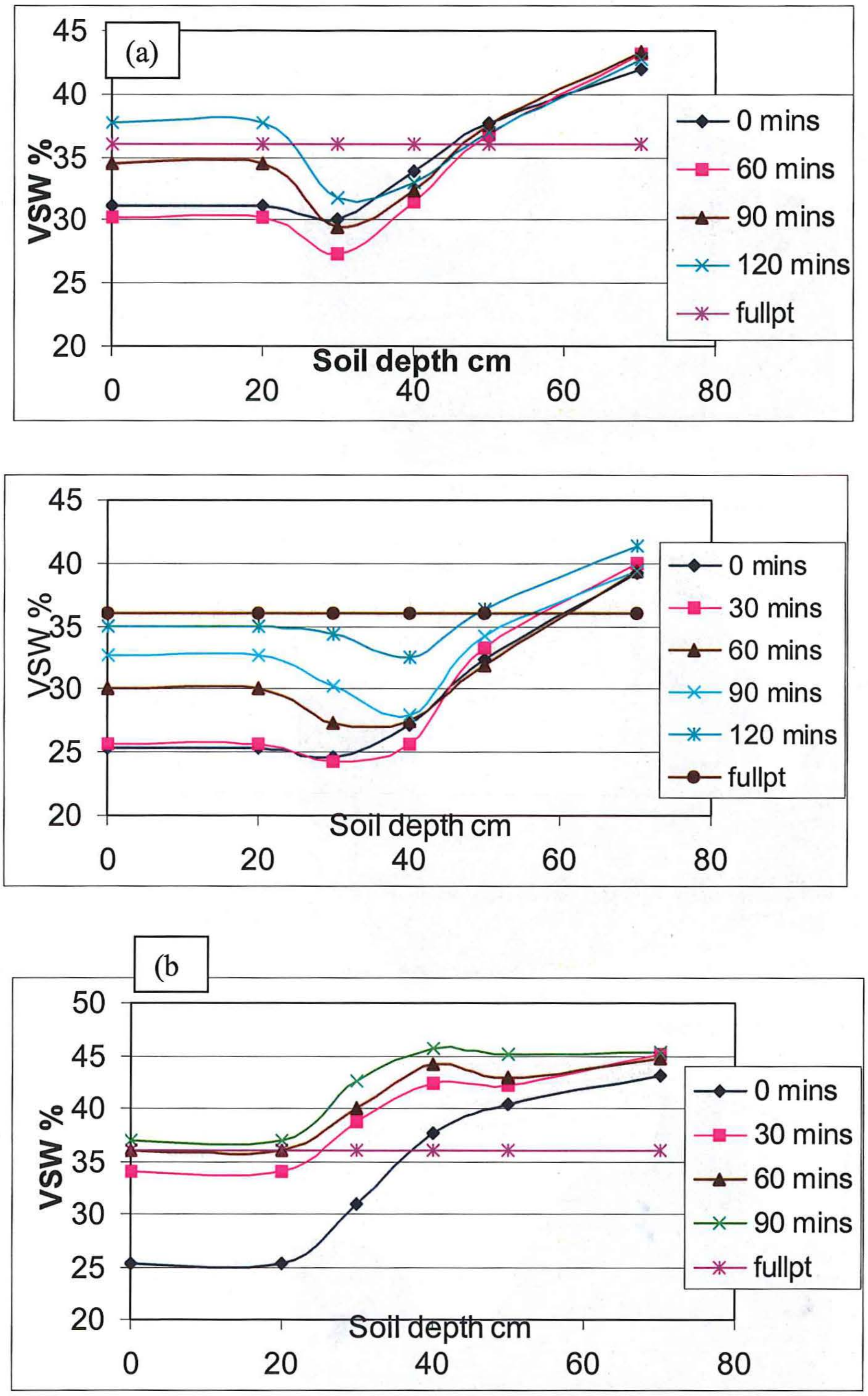
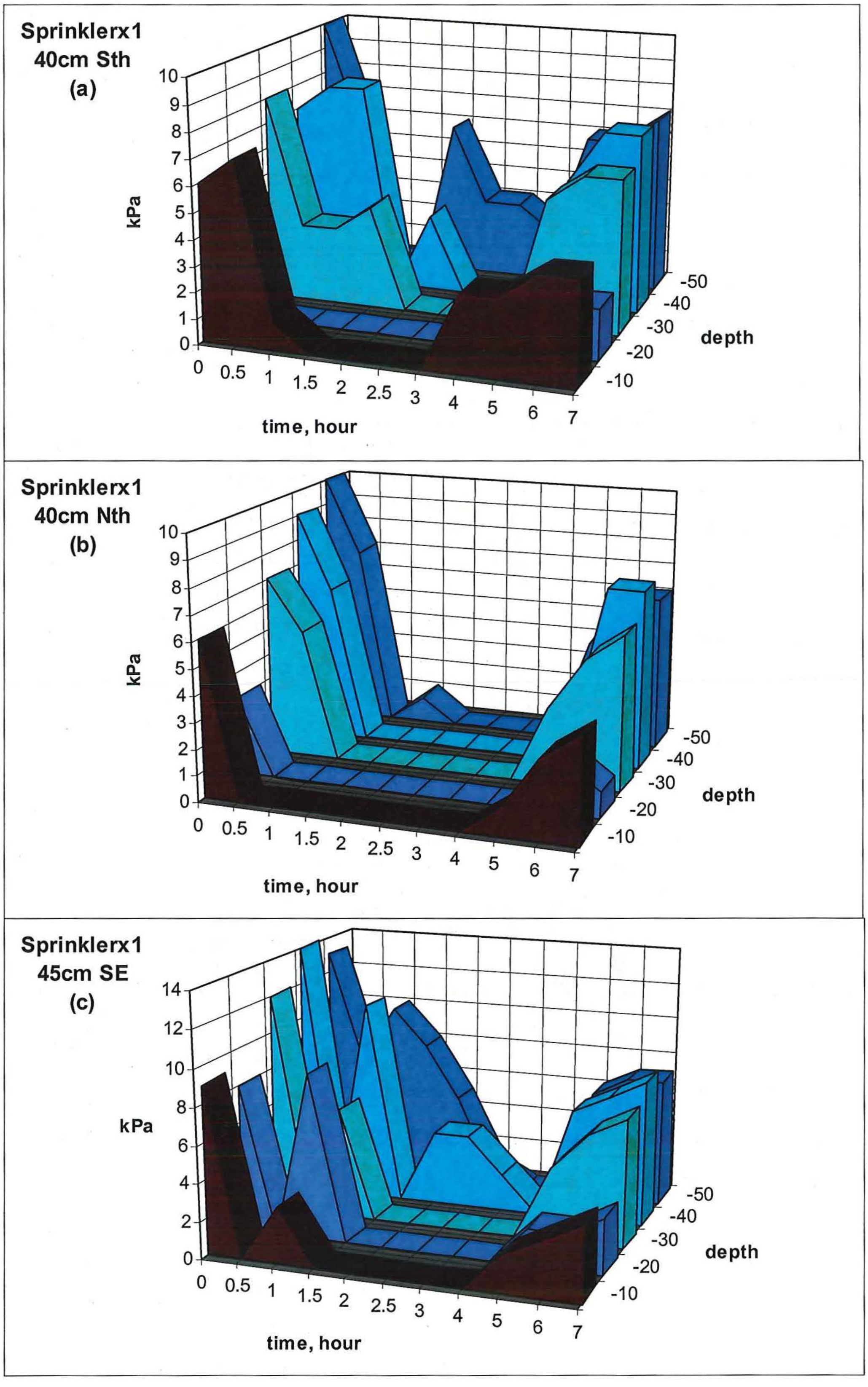
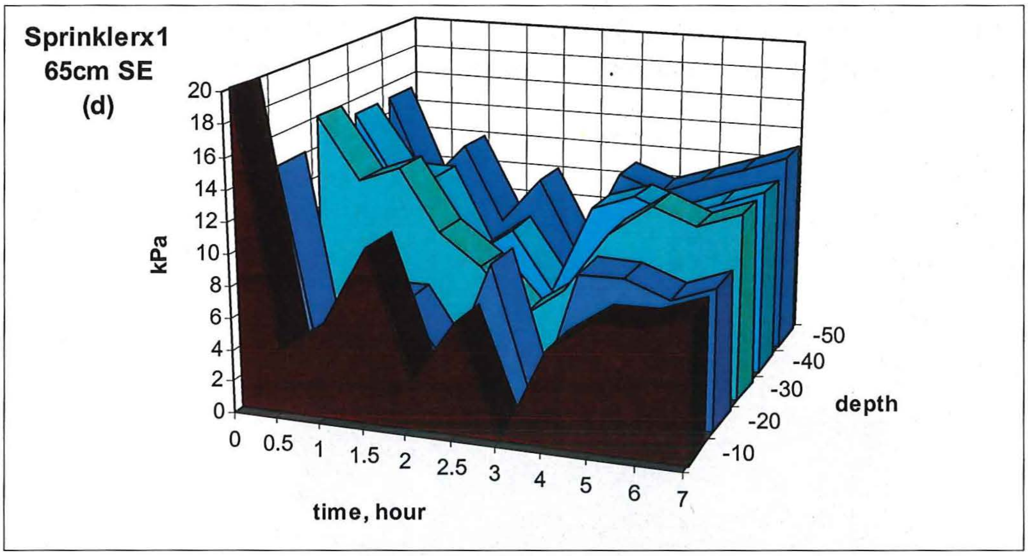


Figure 13: **Changes in soil matric potential (kPa) with depth and time for (a) 40cm Sth (b) 40cm Nth (c) 45cm SE and (d) 65cm SE from the sprinkler.**

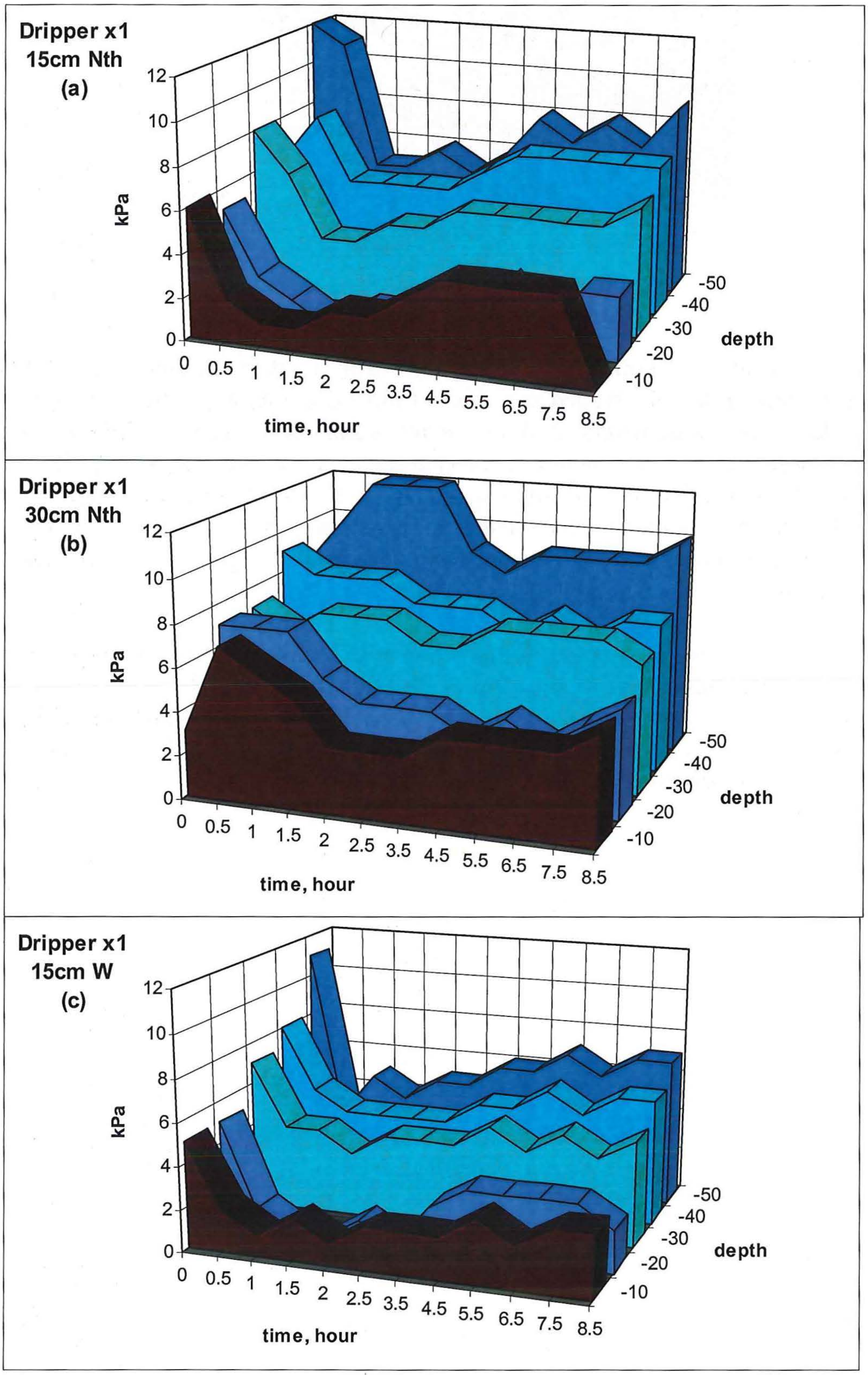


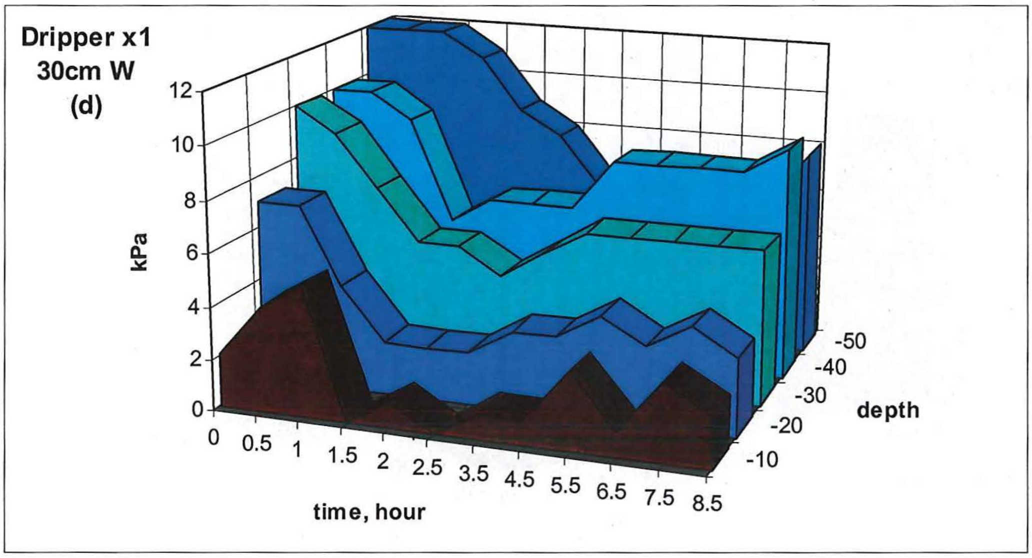


The movement of the wetting front through the soil at selected points (Figure 13) shows variability across the wetted area. Part of this variability arises from sensitivity issues relating to tensiometers, and the actual variation in sprinkler distribution patterns. Tensiometers were found to be very responsive, dramatically changing over 30 minute intervals. By the end of irrigation at 2 hours all depths and locations indicated saturated conditions, which rose after irrigation ceased, with a delay of about 1-2 hours. This data suggests that tensiometers in this soil are highly responsive to soil moisture changes.

Single drip irrigated plants (Figure 14) show that at 15 cm from the emitter, wetting of soil with time was faster and to a greater depth than at 30 cm. After only 1 hour of irrigation the wetting front was beyond 50 cm at a distance of 15 cm form the emitter. At 30 cm distance, the wetting front reached the fringes of 50 cm depth as low but not saturated moisture potentials were measured.

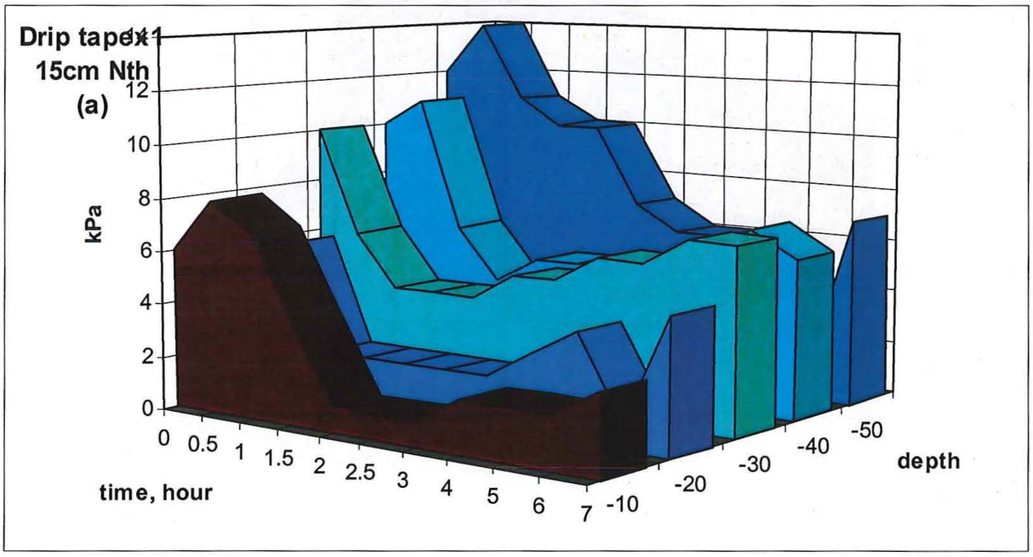
Figure 14: **Changes in soil matric potential (kPa) with depth and time for (a) 15cm Nth (b) 30cm Nth (c) 15cm W and (d) 30cm W from the emitter.**





For single drip tape (Figure 15) midway between emitters at 15 cm spacing, after 2 hours of irrigation the wetting front had penetrated to about 50 cm depth. For double drip tape irrigation (Figure 16) the wetting front had reached 50 cm at about 2.5 hours at 15 cm north and 20 cm west of the centre point of 4 emitters; at 2.5 hours 15 cm south of the centre point; and at 2.5 hours 35 cm west of the centre point.

Figure 15: Changes in soil matric potential (kPa) with depth and time for (a) 15cm Nth (b) 15cm W from the emitter.



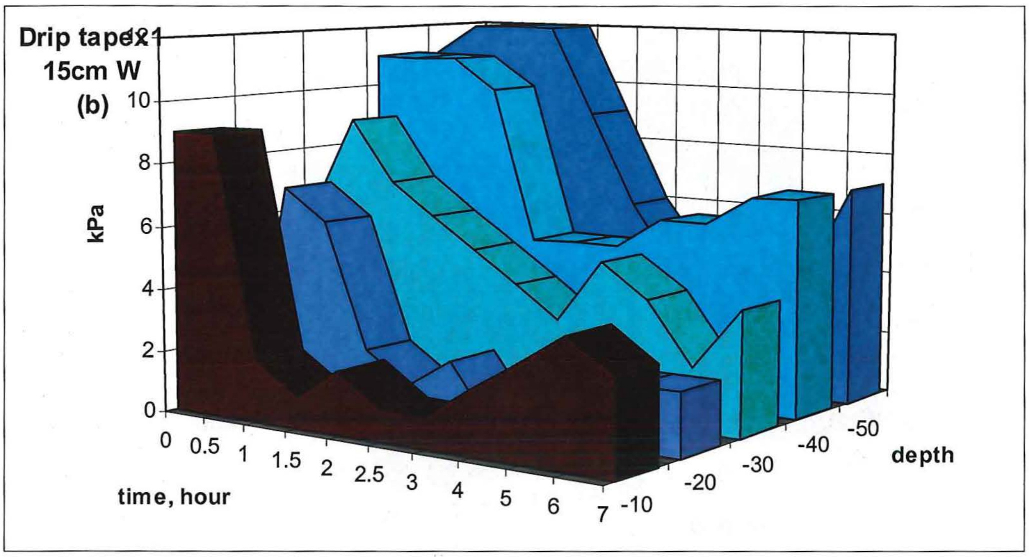
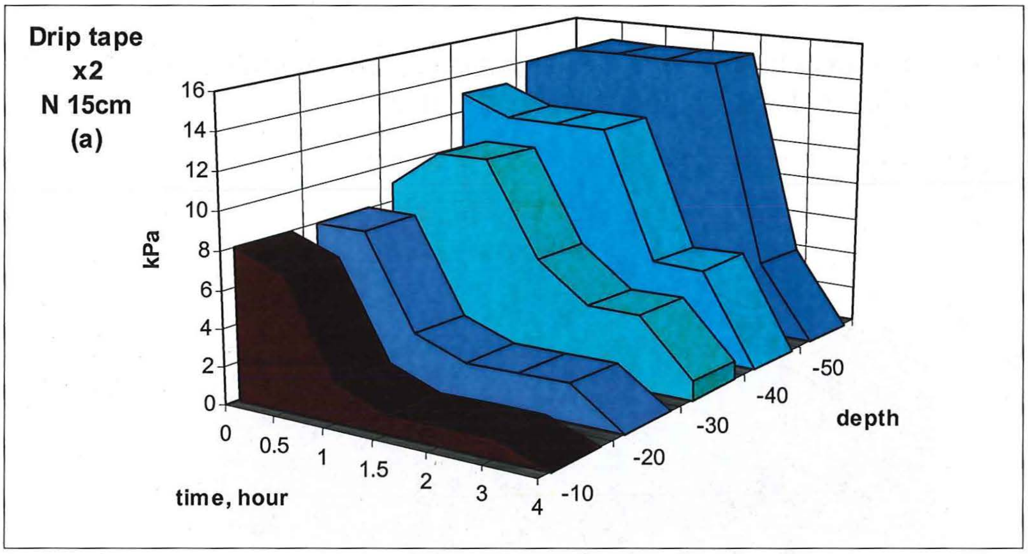
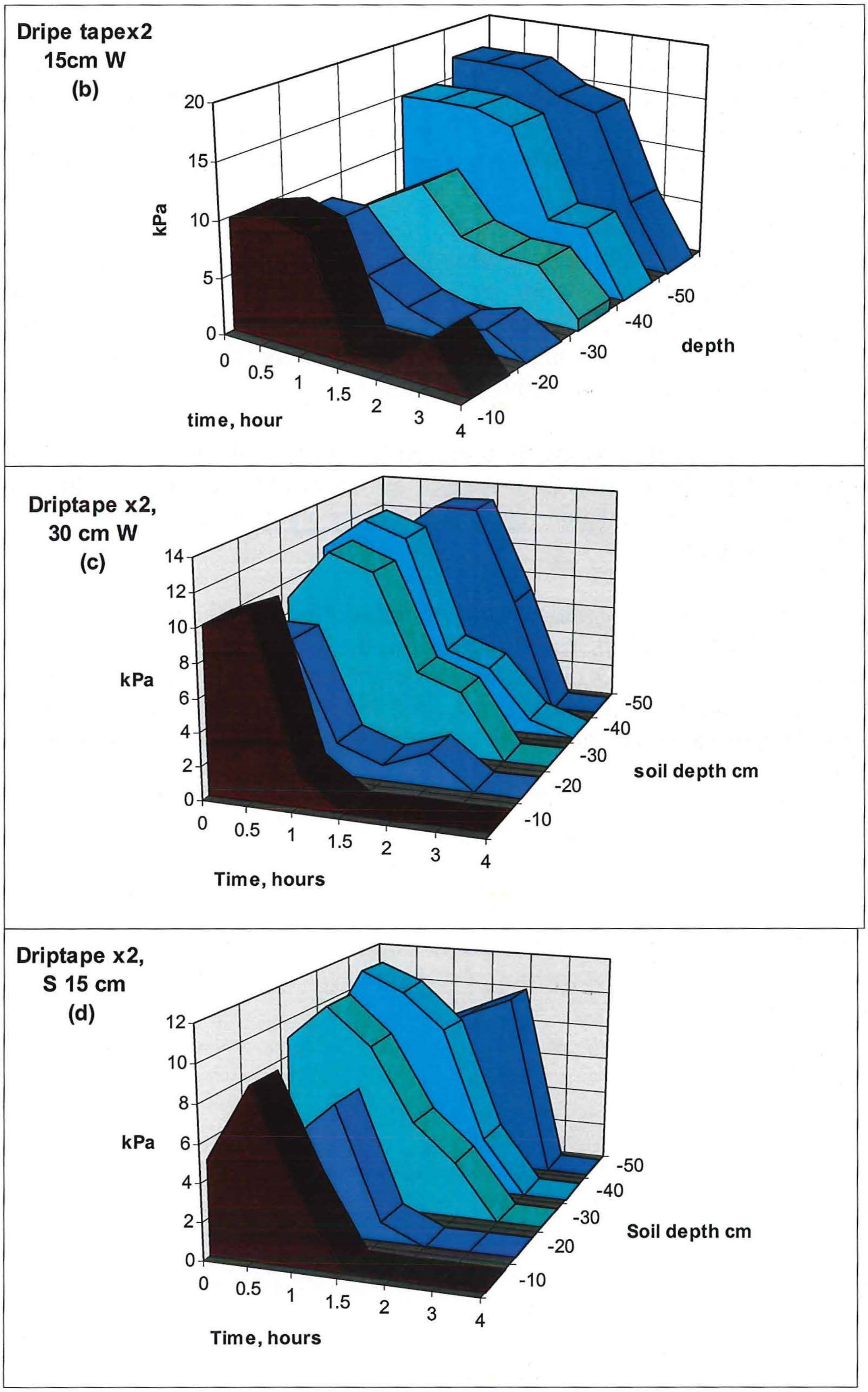


Figure 16: **Changes in soil matric potential (kPa) with depth and time for (a) 15cm Nth (b) 15cm W (c)30cm W and (d) 15cm Sth from the emitter.**





It is very difficult to make conclusions from this data due to the lack of replicates and the complexity associated with having active root systems influencing measurements of soil water status. Despite these limitations, it is possible to make some quite general conclusions that will impact on the management of different irrigation systems, achieved by using different emitters or sprinklers. These are best listed in point form:

- Sprinkler wetting patterns are notoriously variable and the gross precipitation rate should be used or the mean of catch cans radially from the sprinkler. Close to the sprinkler (<50 cm) wetting front movement to 50 cm was achieved in about 1 hour, at distance >50 cm the soil was not saturated beyond 20 cm depth even after 2 hours of irrigation.

- Single button drippers (8L/hour) wet the soil faster at 15 rather than 30 cm radially from the emitter, and after 1 hour, the soil was saturated to 50 cm depth 15 cm from the emitter and after 2 hours to 50 cm depth, 30 cm radially from the emitter. Single button drippers have high precipitation rates and thus the potential for drainage losses is high unless carefully monitored.

- For single drip tape the wetting front moved to 50 cm in about 2 hours, and for double drip tape the wetting front reached 50 cm in about 2.5 hours. The drip tapes have slower precipitation rates than drippers and thus less likely to cause localised drainage losses.

- Maximum wetted areas are achieved after 1 hour of irrigation for all the emitters. For 8L/hour button drippers irrigation duration should not exceed 40 minutes duration, and for drip tape <2 hours, on soils of similar porosity to that studied. For sprinklers the gross precipitation rate (litres/hour/wetted area) should be used to determine irrigation duration, but irrigation times are likely to be 3 to 4 hours safely.

CHAPTER 5: AN ASSESSMENT OF PAPAYA IRRIGATION SYSTEMS, IN NORTH QUEENSLAND.

5.1 INTRODUCTION

The understanding and awareness of irrigation scheduling and soil water management by horticultural irrigators in North Queensland, is generally poorly developed. The papaya industry is a large water user, with the range in peak water consumption being 50 to 600 litres per tree per week, despite annual rainfalls exceeding 3000 mm (Richards *et al.* 1995). A survey of papaya growers practices by Richards *et al.* (1995) revealed that less than 20% of growers used tensiometers or other scheduling devices, and that 90% of growers used micro-sprinklers and 10% used drip irrigation emitters. All horticultural industries are expanding in this region and past complacency on irrigation management issues needs to be replaced with education, training and awareness. Part of this process will involve the industry uptake of improved irrigation systems such as that presented in the paper following.

The issue of sustainability in farming systems is often poorly defined and understood. In this paper sustainability means 'an improvement in the productive performance of a system without depleting the natural resource base upon which future performance depends' as defined by Pandey and Hardaker (1994). The economic component is added to emphasise that systems have little chance of being adopted without a measure of economic benefit being possible over the short or long term.

The aim of this study was to compare and contrast the performance of papaya growth and yield under different watering regimes. Performance was assessed for each system using bio-physical factors of yield, growth, fruit quality, water usage and drainage, and each system was assessed on its economic merits as well.

5.2 MATERIALS AND METHODS

5.2.1 LOCATION, CLIMATE AND SOIL PROPERTIES

An irrigation trial with papaya (*Carica papaya)* plants, was conducted at the Queensland Horticulture Institute at South Johnstone, North Queensland, Australia (17 ° 36' 30" S, 146 ° 00' 30 " E) from January 1996 to March 1997. Details of monthly weather data from January 1996 through to March 1997 are shown as Figure 17.

Treatments were established using papaya 1B hybrid plants, planted to the field in October 1995, with irrigation treatments and scheduling commencing in January 1996. Planting density was 1650 plants per hectare, in single lines at 4m intervals and with 1.5 m plant spacings. Lines were mounded at 0.4m height and 2m width at the base.

The soil type is described as a Mundoo series Krasnozem (Great Soil Group) and as a Tropeptic Haplorthox (Soil Taxonomy) and physical properties presented as Table 6.

Figure 17: Mean monthly maximum and minimum temperatures, and total monthly evaporation and rainfall, from SJRS January 1996 to March 1997.

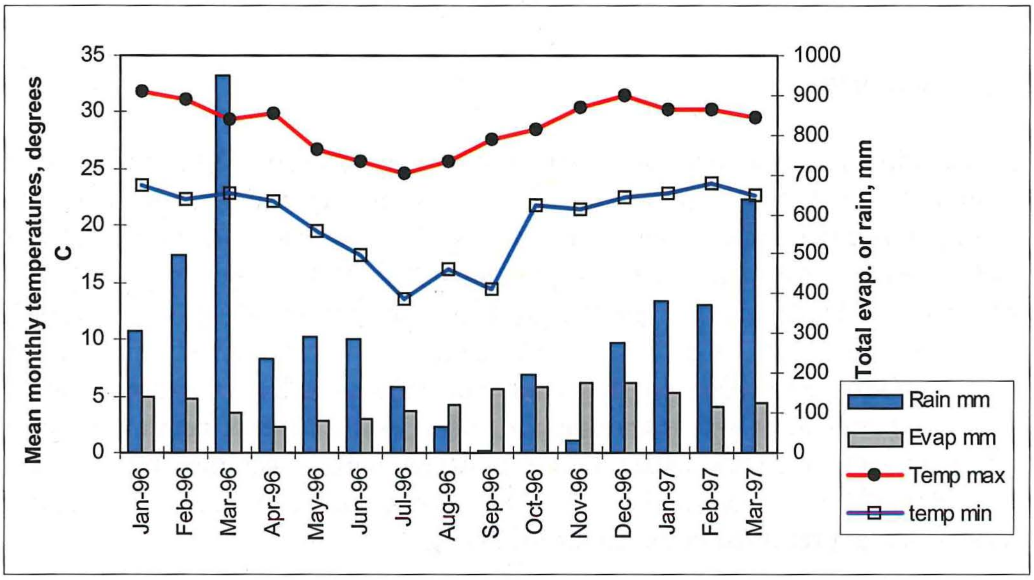


Table 6: Soil physical properties of Mundoo Krasnozem .

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Bulk Density (g/cm^3)	θ_v (%) at -10 Kpa	θ_v (%) at -1500 Kpa
0-20	68	17	15	1.26	40.5	22
20-40	76	15	10	1.27	41.1	23
40-60	77	13	10	1.33	43.2	24
60-80	77	12	10	1.33	42.5	24

5.2.2 Experimental design, Irrigation treatments and scheduling details

The trial was a randomised complete block design, with 2 blocks (replicates), 12 treatments and 15 trees per treatment plot. Six irrigation emitters and sprinklers corresponding to six wetted areas were chosen, and two rates of watering (high and low) selected. The full point or upper storage limit was set at 155 mm water per 40 cm depth (rooting range) and two refill points set at 123 mm (50% depletion of AWC = high rate, non stressed (Richards 1997)) and 89 mm (the permanent wilting point storage limit = low rate, stressed). Details of treatments are shown as Table 7, with treatment short codes in parentheses. Soil moisture storage status S, mm/40 cm depth, was determined twice weekly using a CPN neutron moisture probe, which was calibrated previously (Chapter 2). Values of S were used to decide irrigation duration, using either of the two refill points and the full point as thresholds for irrigation decisions. As far as possible, high treatments were kept at least above 123 mm S, and low treatments allowed to dry down to 89 mm S. As a consequence, irrigation applied per treatment reflects quite accurately water requirements under continuously moist or drying moisture regimes. Records of irrigation hours were kept and irrigation meters were installed in July 1996 to record water flow for each treatment row.

Table 7: Irrigation treatments and irrigation parameters.

Treatment and emitter type	Water rate	Flow rate L/hour/plant	Wetted aream^2 /plant	Totallitres /plant*	Total ML /ha*	Total depthof irrigation mm*	Irrigation as % ofrain and irrigation	Gross Precip. rate mm/hour
micro sprinklershared (T1)	high	20	3.5	4073	6.72	1358	24	6
micro sprinkler shared (T2)	low	20	3.5	3138	5.17	1046	19.7	6
micro sprinkler per tree (T3)	high	39	7	7886	13.0	1352	38	6
micro sprinkler per tree (T4)	low	39	7	2321	3.83	398	15	6
Dripper 1/ tree (T5)	high	8.8	0.19	675	1.11	3018	5	38
Dripper 1/tree (T6)	low	8.8	0.19	217	0.36	969	1.7	38
Dripper 2/ tree (T7)	high	18	0.38	872	1.44	1745	6.4	38
Dripper 2/tree (T8)	low	18	0.38	777	1.28	1554	5.7	38
drip tape 1 line/row(T9)	high	9.4	0.60	1211	2	2318	8.6	18
drip tape 1 line/row (T10)	low	9.4	0.60	1072	1.77	2053	7.7	18
drip tape 2 lines/row (T11)	high	19	1.10	2327	3.84	2204	15.4	18
drip tape 2 lines/row (T12)	low	19	1.10	1760	2.9	1667	12	18

* refers to the period July 2nd 1996 to March 30th 1997.

5.2.3 HARVESTING AND FRUIT QUALITY ASSESSMENT

Harvesting commenced 20/06/96 and was completed 25/03/97, some 2 months earlier than planned due to cyclonic activity late in March 1997. Treatment plots were harvested twice weekly to collect fruit yield, number and mean fruit size data. Yield data was reduced to mean yield in kgs per tree. Although each plot commenced with 15 trees each, losses due to phyto-plasma diseases were typically 25%, reducing mean plot size to about 12 trees.

In September and December 1996, and in March 1997, fruits were harvested from selected treatment trees and assessed for size, TSS (^{o} Brix), firmness and eating quality. A minimum of 2 and a maximum of 8 fruits per plot were collected per recording period, and both plots of selected treatments averaged. Firmness was measured using a penetrometer, on fruit halves with 4 measurements per half. Total soluble solids was determined using a hand held refractometer using juice from the petal scar fruit end. Eating quality was assessed by two people using the criteria of 1=very good, 2=good, 3=fair, 4=acceptable and 5=unacceptable.

5.2.4 GROWTH AND BIOMASS PARTITIONING

Growth of trees was recorded as stem girth marked 15 cm above the ground, and as height to the crown, with 4 trees from all treatments recorded fortnightly from 8/02/96 to 27/06/96 and thereafter monthly. Trunk cross-sectional area (TCA) was derived from the stem girth (diameter) measurement. In April 1997 all plants were measured to determine crop load per treatment.

On 8th May 1997, four trees each from treatments T3,T6,T7,T10 and T11 were destructively sampled into components of leaves, petioles, stem and fruits. For all trees individual fresh weights of each component were measured in the field and mixed samples of each component taken for dry matter determination at 70-75° C over 4 days.

5.2.5 Petiole and soil analysis, fertiliser application

In July and October 1996 four petioles per treatment were sampled, oven dried at 65-70° C for 3 days, ground in a hammer mill then analysed. Soil samples (0-15 cm) were collected in October 1996 and March 1997, by collecting 6 cores per treatment, mixing then sub-sampling. Soils were oven dried at 40 ° C for 2 days before grinding and sieving to the <2mm fraction, for analysis. Nitrate N was determined on field condition soil the day after sampling.

Nutrients were applied as either ground applications of NPK (12-12-17) monthly or as monthly fertigation of proprietary NPK soluble products including trace elements (Zn,B,Fe,Mn). Total application rates of macro nutrients (elemental basis) in kg/ha were: N, 254; P, 91; and K 282, which are considered as adequate for this soil. Limestone application (5t/ha) was done in March 1996, and 200g/plant MgO applied in November 1996. Trace element foliar sprays of Zn and B were applied at 3 monthly intervals.

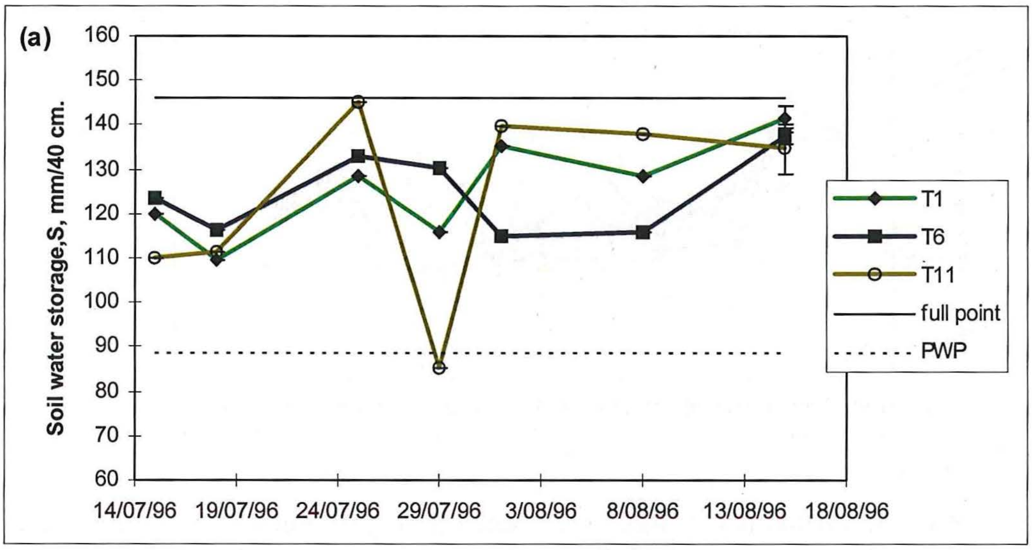
5.3 Results and discussion

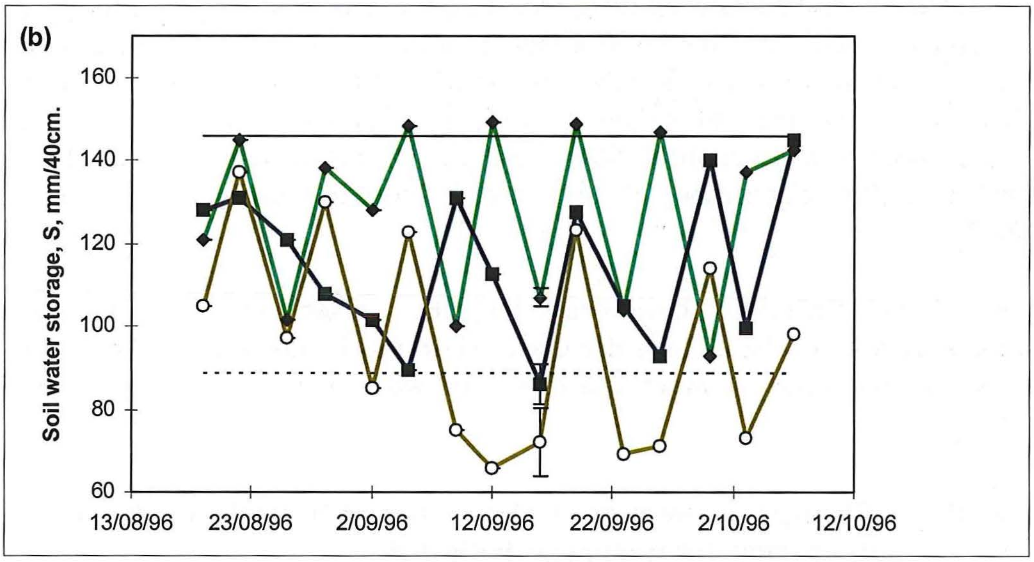
5.3.1 Soil water dynamics

Three periods corresponding to cool and dry, warm and dry and hot and dry, were selected for changes in stored soil water (0-40cm) data presentation as these periods reflect best the effect of applied irrigation treatments. Treatments T1, T6, and T11 were selected to show the diversity in range of stored water over 0-40 cm depth (Figure 18 (a), (b) and (c)).

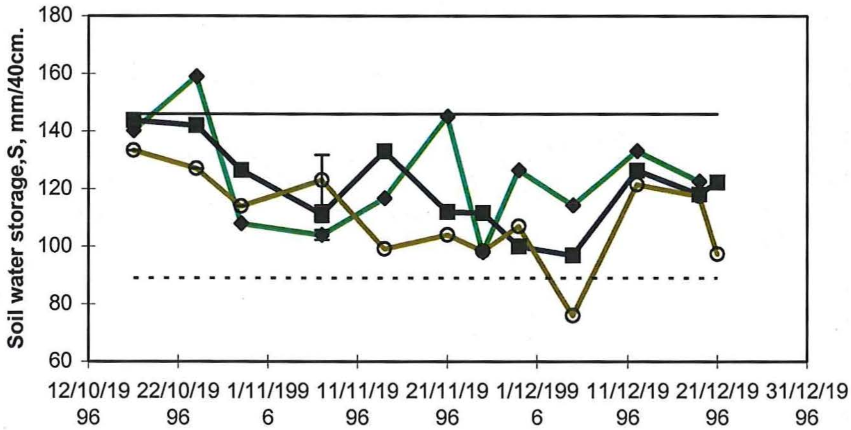
The data show water contents some 1 to 3 days after the previous irrigation, and immediately before the next irrigation. Representative standard errors are shown for one date only, and s.e.'s were lowest for the sprinkler treatments and highest for the drip tape, reflecting variations in water uniformity distribution and neutron probe measuring volumes for drip irrigated plants. Precipitation rates for drippers and drip tape (Table 7) resulted in high percolation rates and it was necessary to split watering time across days for these treatments. It was not feasible to measure daily soil water status with the equipment used, so data collected are indicative of water status only. Scheduling was based upon the draw down of soil water to either 123 mm (high rate) or 89 mm (low rate) thus total litres applied is a reliable indication of water required over the wetted area. Despite careful monitoring, occasionally S for high rate treatments fell below 123mm, and this experience highlights the need to have a continuous soil water sensing system in place, especially where wetted area and rooting depth are small as irrigation will be frequent and short. The most stressful periods (Figure 18 (b),(c)) reveals that treatments T6 and T11 were often near or below PWP, in contrast to treatment T1 which was always more moist. Aiyelaagbe *et al.* (1986) established a -2 bar soil moisture potential (at 30 cm) as the critical level for papaya in Nigeria. In NQ, both the 50% and 100% depletion.

Figure 18: Changes in stored soil water for papaya for (a) Cool and dry period, (b) warm and dry period and (c) hot and dry period, with selected treatments. SE bars are shown for selected points





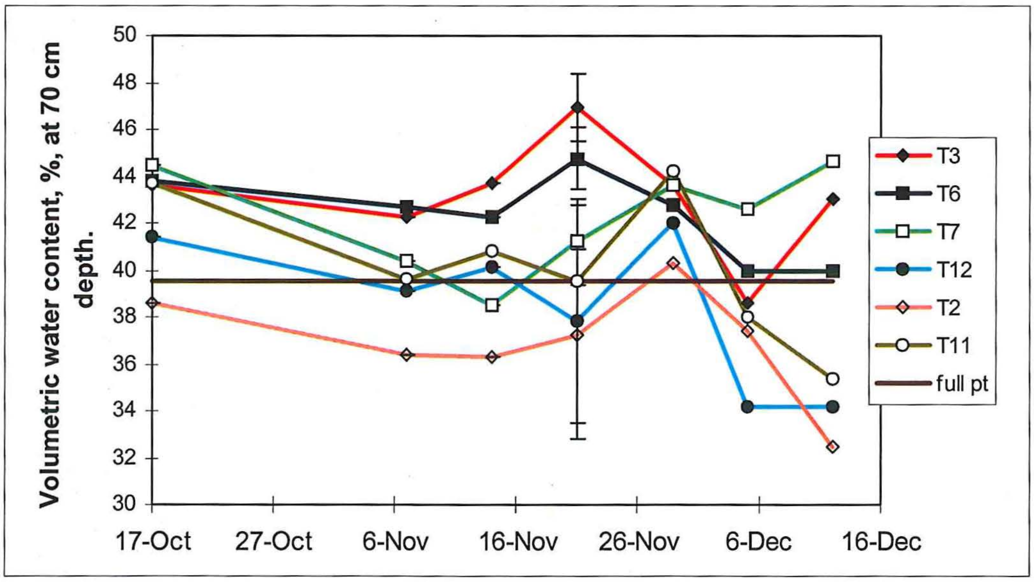
(c)



Treatments were often below this level (based upon proximity to PWP line), and the 100% depletion treatments were often well below it and for a longer period than the 50% depletion treatments for up to 4 days at a time. It was in practice difficult to manage treatments over a wide range of wetted areas to stay within 50% or 100% depletion zones, and the results show this in terms of stored moisture levels measured, small variations in water applied within area treatments (except between T3, T4 Table 7), and the lack of significance of water rates in the statistical analyses of yield data (Table 8).

Drainage beyond the root zone was checked by measurement of θ_v at 70 cm depth, and a range of results for the hot and dry period shown as Figure 19. During this period there was a total of only 42 mm rainfall, thus soil water status should reflect irrigation treatments.

Figure 19: Changes in volumetric water content at 70 cm depth, during a hot dry period, for treatments indicated.

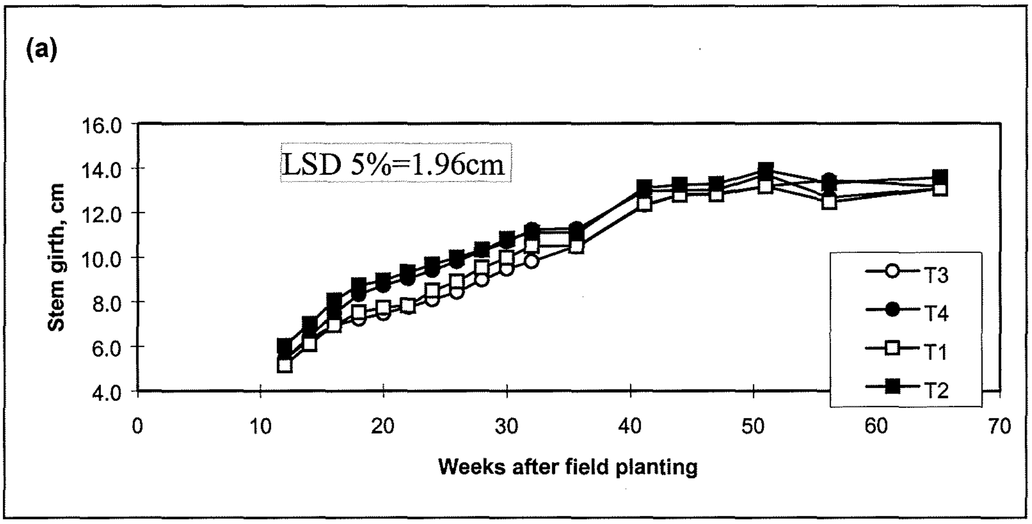


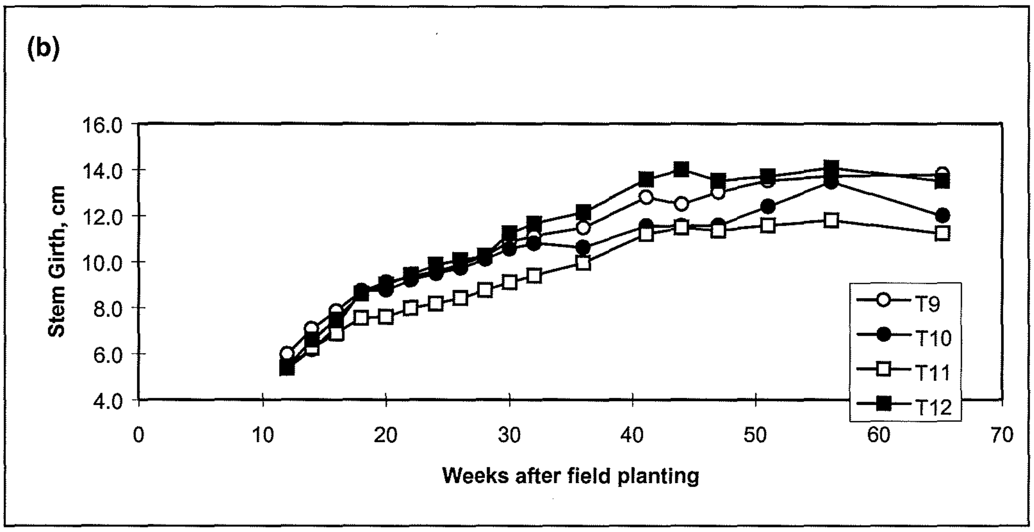
Treatments T2 and T12 had consistently lower θ_v 's at or below the full point line of 39.5% or -15 kPa, with t11 giving a generally wet profile. Treatments T3 and T6 were always wet at 70 cm depth, highlighting the rapid precipitation rate of T6 and the over-watering of T3. Overall, the drip tape treatments and shared sprinkler treatments recorded lower θ_v 's than did either the drippers or single sprinklers. The significance of having θ_v 's higher than 39.5% at 70 cm depth is that drainage rates increase rapidly above this moisture content in this soil (see Chapter 3), thus favouring the movement of both water and nutrients out of the root zone.

5.3.2 GROWTH AND BIOMASS PARTITIONING

Stem girth measured in April 1997 was subject to ANOVA and did not identify any significant effects of wetted area or rate of watering on tree size. There were individual plot differences with t6 treatment trees being significantly smaller than most other treatments. Plots of tree girth are presented as Figure 20 (a),(b) and (c). Rainfall over the trial period was high except in August, September and November (Figure 17) thus major differences due to irrigation treatment have probably been masked. However, non-linear regression analysis (y=a+b/(1+cx)) established a significant relationship of TCA (trunk cross-sectional area) and water applied as shown in Figure 21 (a), with an R^2 value of 0.643. The relationship levels out after 1500 litres per tree, beyond which increases in irrigation litres applied do not affect TCA. Non-linear relationships of TCA and wetted area or water rate were non-existent. Yield was non-linearly related to irrigation litres per plant (Figure 20 (b)) such that maximum yield was attained at about 2,600 litres/tree, and with a minimum wetted area of 1 square metre per plant (Figure 20 (c)).

Figure 20: Changes in stem girth for (a) Sprinkler irrigated plants, (b) drip tape irrigated plants and (c) dripper irrigated plants.





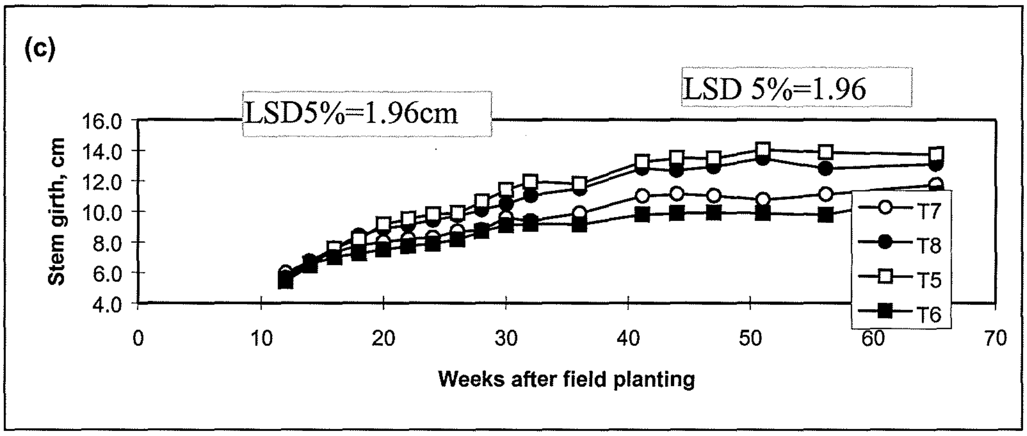


Figure 22 shows the distribution of dry matter components across a range of irrigation treatments. Total dry matter was least for T6 treatment and similar for the others regardless of wetting pattern or area wetted. Components percentage of total dry matter changed little over the treatments studied with stems consistently comprising 60-68% of total tops dry weight and petioles the least (5-7%). Fruit weight was 30-40% of total dry matter indicating a high efficiency of fruit production exists in papaya. Overall, the minor differences in plant growth for all treatments except T6, indicate that plants were not consistently stressed, in relation to applied irrigation and rain waters.

5.3.3 Yield Responses

Treatment mean yields and fruit sizes for 10 treatments are shown as Table 8. Treatments T9 and T11 were omitted from ANOVA as one plot from each treatment had very low yields (<35 kg/tree) in contrast to its other replicate plot which had high yields (>65 kg/tree). Apart from these two treatments for which an explanation of such variability is not available, all other plot pairs showed acceptable variation as detailed in Table 8. In performing statistical analyses for yield it was necessary to eliminate these two treatments from analysis as the variation within treatments was too high, thus all regression models used 10 treatments only.

Table 8: Mean yield, fruit size, WUE and crop load from irrigation trial treatments.

Treatment	mean yield kg/tree	yield t/ha	mean fruit size, g /fruit	Water use efficiency g fruit/litre irrigation	Crop load g/cm^2
T1	61.45a,c	91.25	1180a	26.4	463
T2	62.40a	92.66	1175a	19.9	534
T3	54.10a,d	79.85	1170a	6.9	419
T4	55.35a,c	81.69	1155a	23.8	427
T5	48.70a,d	71.88	1060a	72.1	367
T6	20.70 b	30.55	830b	95.5	255
T7	39.59 d	58.43	1025a	45.4	383
T8	46.40 ,d	68.48	1040a	59.7	463
T10	46.75a,d	69.00	1080a	43.6	397
T12	46.55a,d	68.70	1130a	26.4	389
LSD 5%	16		190		

nb: same letters in a column following data are the same for non-significant differences.

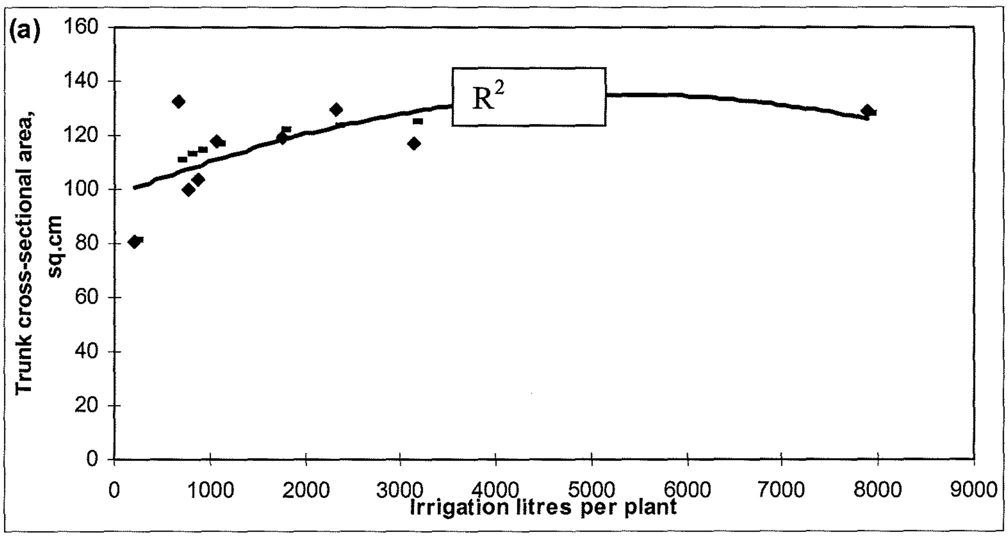
Lowest yields were obtained with drip irrigated trees (T6, T7) and highest yields with sprinkler irrigated trees (T1, T2). However treatments T3, T4, T5, T10, T12 produced yields which were not significantly different from either T1 or T2 at 5%. Using LSD 10% (13kg) T1 and T2 are both significantly larger than all other treatments except T3 and T4. Drip tape either single or doubled, produced results similar to two drippers per tree or single dripper irrigated at the high rate. Of interest also is that one sprinkler shared with two trees at either rates (T1, T2), produced slightly higher yields than did one sprinkler per tree(T3,T4). With the exception of single drippers, irrigation rate had no effect on yield. Layne *et al.*(1996) could not detect any peach yield advantages of micro-sprinkler or drip irrigation , but tree size was larger for drip irrigated trees. Awada *et al.* ( ) reported the results of drip irrigation treatments on papaya yield in Hawaii, finding a range in yield from 47 to 69 kg/tree , with optimum water use at the average rate of 93L/tree per week. These results compare well with yield results obtained in NQ, and optimum water rates lower at 2600 litres/tree or 70 litres/tree/week (Figure 21 (b)). For shared sprinklers the actual maximum weekly water application was 220L/tree in November, and for double drippers 76L/tree and for single driptape 73 L/tree.

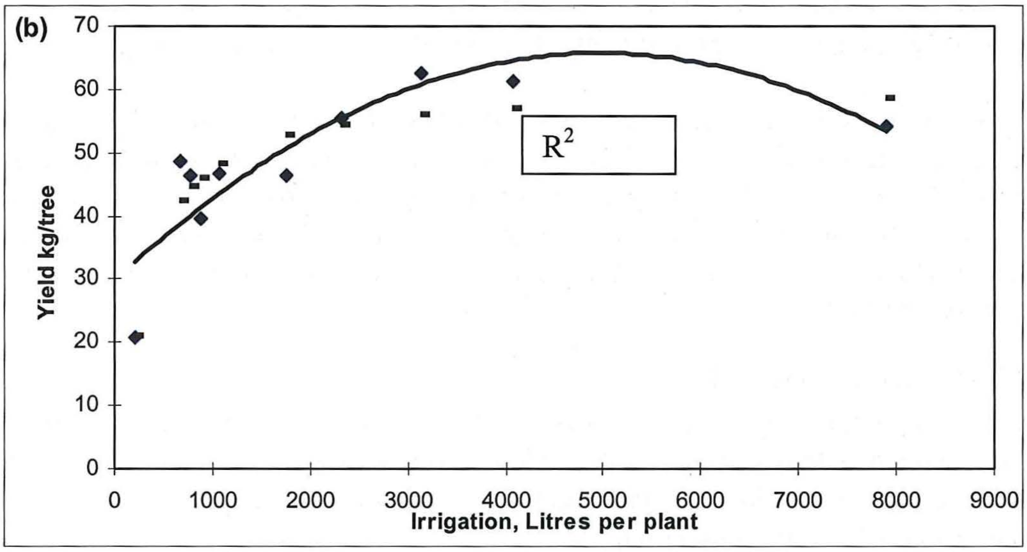
Table 9: Estimates of weekly, peak water consumption in November 1997 for different systems and associated crop factors.

	Irrig. hours	Water L/tree/week	Wet area /tree	Irrig mm (6 m ^{2})	Irrig mm (wet area)	K_c (6 m ^{2})	K_c (wet area)
Sprinkler-shared	11	220	3.5	36.6	63	0.89	1.54
Sprinkler single	6.2	250	7	41.6	35.7	1	0.87
Drip tape single	7.8	73	0.6	12.2	122	0.29	3
Double drippers	4.2	76	0.38	12.7	200	0.31	4.9
Double drip tape	5.2	100	1.1	16.7	91	0.41	2.2

Table 9 shows the problems to be encountered when trying to measure a crop factor for partial soil wetting. For 7 days pan evaporation of 41 mm, for shared sprinklers the crop factor could either be 1.54 or 0.89 according to area basis chosen to calculate irrigation depth applied. For 41 mm E over 6 square metres per plant (1.5m x 4m), actual potential ET would be 246 litres per tree. In order to use these results meaningfully for other soils, it would be necessary to indicate water requirement on the wetted area basis, otherwise underwatering may result. For sprinkler irrigated plants K_c is likely to be in the range of 0.87 to 1.54.

Figure 21: Effect of irrigation litres/plant on (a) Trunk cross sectional area, (b) Papaya yield kg/tree, and (c) the effect of wetted area on papaya yield. Non-linear regression values are indicated.





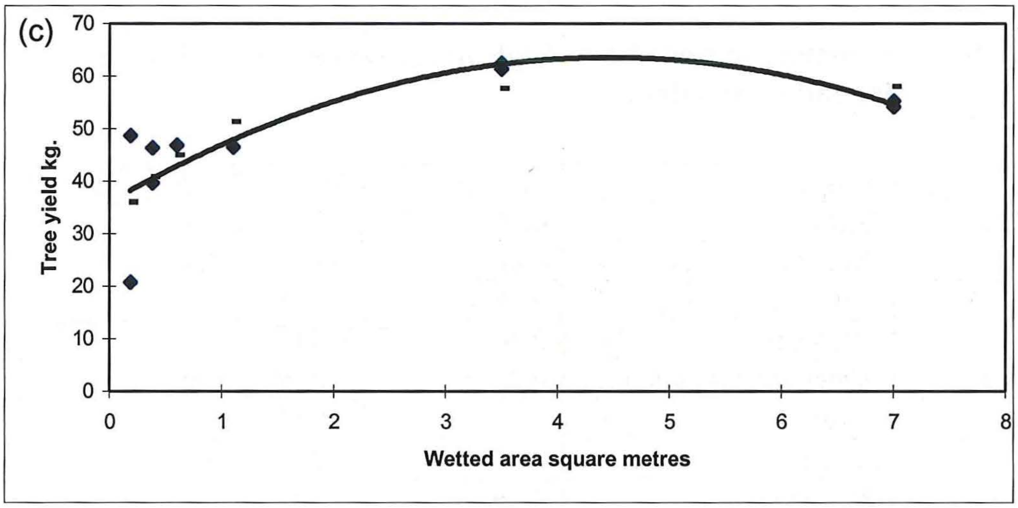
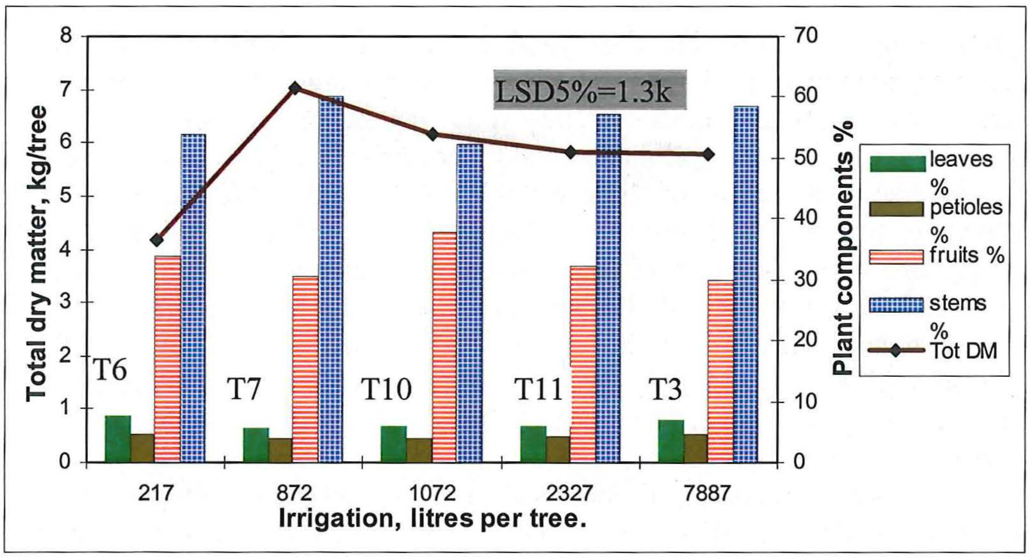


Figure 22. Variation in total dry matter per tree and percentage dry matter components, for different irrigation treatments.



Crop loads, which are a surrogate measure of the diversion of water and food into fruit production, indicated that sprinkler irrigated trees had the highest efficiency of fruit production. Treatment T6 with the highest WUE had by far the lowest crop load, confirming that such a high WUE was associated with reduced water supply.

Fruit size was sensitive to wetted area but not rate of irrigation, with single dripper treatments having significantly smaller fruit size than all other treatments (Table 8). Water use efficiency (WUE= fruit yield/water applied) was strongly inversely related to litres of irrigation per tree, with the T3 treatment being by far the least efficient irrigation system, and T6 the most efficient. WUE increases rapidly below <2,000 litres per tree applied.

5.3.4 REGRESSION ANALYSIS

Several multiple linear regression models and non-linear regression models using yield, fruit size and tree size as the dependent variables were examined, in order to establish the cause of variance in yield and to establish relationships. The results are shown as Table 10 and Figures 21 a,b and c.

Table 10: Summary of stepwise multiple linear regression analysis of irrigation trial data.

Dependent Y	Added X	P(%) for R^2	R^2	P(%) for added X
Yield	Girth	0.15	0.7353	0.72
	Precipitation rate	0.08	0.8677	1.93
	soil water storage limit	0.18	0.9047	7.09
	litres/tree	0.34	0.9368	N.S.
Fruit size	Water use efficiency	0.03	0.825	0.03
	Girth	0.00	0.9854	0.01
	litres/tree	0.00	0.9911	0.59
	Wetted area	0.00	0.9973	1.93
Girth	Precipitation rate	13.13	0.2610	N.S.
Height	Wetted area	22.9	0.1752	N.S.
Crop load	Water use efficiency	2.09	0.5072	2.09

Table 10 indicates the dependence of yield on tree size (girth), with additional influence of irrigation precipitation rates. Soil water storage limit is marginally significant (10% level) and litres per tree total application not significant. The regression coefficients for precipitation rate and litres per tree were negative indicating inverse relationships of these variables with yield. WUE and girth, with minor effects of litres/tree and wetted area largely determined fruit size. Both WUE and litres per tree gave negative coefficients pointing towards inverse relationships of fruit size with these variables, such that a small water application as per T6 (and thus high WUE) produced smaller fruit, due to increased competition by developing fruits for water and nutrients. No significant and meaningful relationships could be ascribed to either height or girth. The efficiency of fruiting as determined by crop load was weakly, inversely related to WUE.
The strong non-linear relationship of yield and litres applied per tree (Figure 21 (b)), with maximum yields attained at about 2500 litres per tree, was best matched by the single sprinkler treatment (T4) or the double drip tape treatments (T11). This relates to

a weekly average over the period of 70 litres per tree, and points to a rapidly increasing yield outcome as litres applied approaches this level. A weaker non-linear effect of wetted area on yield (Figure 21 (c)), suggests an optimum wetted area is reached at about 1 square metre per plant. This corresponds to the double drip tape treatments. Bravdo *et al.*(1990) found that a reduction of wetted soil volume (drippers vs. sprinklers) did not reduce citrus yields.

Figure 21 (a) showed the non-linear response of TCA to litres applied per tree, with little change in TCA beyond 1500 litres per tree. From Table 10, 73% of yield response in this trial can be related primarily to changes in tree size (girth or TCA), and tree size is largely determined by irrigation applied (64.3% of response, Figure 21 (a)). Secondary influences determining yield are related to irrigation treatments, and collectively they account for 17% of yield response. In contrast, non -linear models (Figure 21 (b)) suggests yield is well related to water applied (84.2%). The weakness of this model is that water applied does not relate directly to soil water status or PAWC, due to variations in wetted area, depth, and drainage losses.

Fruit size response (82%) was explained by WUE with tree size and irrigation treatment accounting for a further 17% of the response. Although the WUE parameter was inversely related to fruit size, the range in fruit size over all treatments was not limiting from a marketing viewpoint. Treatment T1 gave a relatively large fruit size, highest mean yield, medium to low WUE and a high crop load, whereas T6 gave the lowest yield, smallest fruit size, highest WUE and the lowest crop load (Table 8). It is evident that a high efficiency of irrigation (WUE) is associated with reductions in yield, fruit size and yield efficiency (crop load), but the medium to high range of yields will have the optimum combination of all these parameters. This is an argument for the drip tape and shared sprinkler treatments as being more suitable for papaya irrigation, although the high annual rainfall and soil type make broad generalisations difficult.

5.3.5 FRUIT QUALITY ASSESSMENT

Fruit sampling at three dates (data not shown) confirmed the results of harvesting in establishing significantly smaller fruit size associated with single drip irrigation, at the low rate. The other treatments tested were consistently similar. Total soluble sugars was significantly higher for single dripper (T6) in March, although all samples tested at the medium level only (8.4-9.4%). Firmness of tissue was significantly higher on one occasion only in October for single dripper treatment than other treatments. For all other times there were no differences in tissue hardness. Eating quality changed little over treatments and sampling times, indicating a lack of response to irrigation treatments.

Overall, it appears that irrigation treatments had little impact on papaya fruit quality over a wide range of wetted areas and application rates of irrigation. Quality of lemons was similar in three irrigation treatments studied by Domingo *et al.* (1996), and in muskmelon no significant irrigation treatment effects were noted on fruit quality (Hartz, 1997). Deficit irrigation in peach however, was found to produce smaller fruits with higher TSS (Crisosto *et al.* 1994), which is in line with the results for treatment T6.

5.3.6 NUTRIENT STATUS

Petiole analyses averaged over July and October 1996 and across water rates showed little difference in treatment effects on macro-nutrient concentrations (Table 10). All treatments indicated adequate status of nutrients, with the exception of foliar P(%) which was a bit lower than desirable, and soil analyses (data not shown) indicate non-limiting levels of major soil nutrients and pH. However March 1997 soil analyses showed an imbalance of Ca/Mg in the soil in favour of Mg, presumably as a consequence of MgO application. This was found in all treatments, but K levels were uniformly high.

Table 11: Mean petiole (July/October 1996) concentrations of macro-nutrients averaged over rates of watering within treatments.

Treatment...		N (%)	P (%)	K (%)	Mg (%)	Ca (%)
T11, T12	mean	1.37	0.19	2.32	0.59	2.45
	se	0.16	0.02	0.59	0.04	0.38
T9, T10	mean	1.44	0.19	2.34	0.52	2.34
	se	0.06	0.01	0.55	0.02	0.38
T1, T2	mean	1.33	0.21	2.27	0.62	2.25
	se	0.09	0.02	0.54	0.01	0.40
T3, T4	mean	1.41	0.21	2.49	0.61	2.57
	se	0.18	0.01	0.82	0.04	0.44
T7, T8	mean	1.39	0.20	2.72	0.50	2.78
	se	0.06	0.02	0.57	0.02	0.27
T5, T6	mean	1.46	0.18	2.96	0.59	2.43
	se	0.06	0.01	0.56	0.10	0.24

5.3.7 ECONOMIC COMPARISONS

In order to assess the economic sustainability of treatments evaluated in this trial, costs of installing the systems, pumping and water purchases, assuming water is sourced from an irrigation area, were calculated and compared. All costs are on a per hectare basis, and installation costs allow for different emitter or sprinkler, lateral, mains, sub mains, filtration and pump costs. Pumping costs were estimated at $100/ML and water costs at $22/ML.

Table 12: Comparisons of irrigation installation and operating costs (AUD) per hectare, for the six different systems evaluated.

System	ML/ha * to apply	Water cost $	Installation costs $	Pumping costs $	Total costs$/ ha	Total costs$/ 10 ha
Sprinkler shared T1	8	176	7963	800	8909	89,090
Sprinkler shared T2	6.2	136	7963	620	8719	87,190
Sprinkler x1 T3	15.6	343	10529	1560	12432	124,320
Sprinkler x1 T4	4.6	101	10529	460	11090	110,090
Dripper x 1 T5	1.3	29	6311	130	6470	64,700
Dripper x1 T6	0.43	10	6311	43	6364	63,640
Dripper x2 T7	1.7	37	7273	170	7480	74,800
Dripper x2 T8	1.6	35	7273	160	7468	74,680
drip tape x1 T9	2.4	53	6107	240	6400	64,000
drip tape x1 T10	2.2	48	6107	220	6375	63,750
drip tape x2 T11	4.6	101	7751	460	8312	83,120
drip tape x2 T12	3.5	77	7751	350	8178	81,780

* The above water use (ML/ha) is derived from Table 7, adjusted by adding 20% of water use to account for water use from November 1995 to June 1996, and a total from November 1995 to March 1997.

The cost advantages of dripper and drip tape treatments is apparent from Table 12, as is the high cost of sprinkler designs of treatments T3 and T4. As expected, installation costs are by far the largest cost, although operational costs for T3 are comparatively high.

5.3.8 IRRIGATION TREATMENT EVALUATION

In the light of preceding results and discussion it is valid to try to categorise all treatments studied on the basis of agronomic performance, environmental risk and economic outcome to arrive at combined assessment of the treatments potential. Agronomic performance was rated from 1 to 20 based on relative yields (100%=20); Yield g/L irrigation from 1(low) to 10 (high) ; $ return per KL irrigation 1(low) to 10 (high). Environmental risk was based upon total ML/ha applied with 2 (high) and 20 (low); drainage risk at 70 cm with 5 (high θ_v 's) and 10 (low θ_v 's). Economic outcome was assessed as 2 (low gross margins/ha) and 20 (high gross margins/ha), for the additional irrigation costs. Total scores were tallied out of 90 maximum. The measures (Table 13) chosen to categorise each treatment provide a meaningful way to simultaneously assess a wide range of factors that determine the optimum irrigation system, for a given soil type, climate and crop combination.

Table 13. The assessment of irrigation systems based upon agronomic, environmental and economic performance indices.

System	Yield t/ha	Yield g/ L irrig	$return /KL irrig	Water applied ML/ha	Drainage potential >40cm	Gross margins $/ha	Overall ranking
Drip T5	71.9	72.1	66.37	1.3	Mod	22290	1
Sprinkler T2	92.7	19.9	17.93	6.2	Low	28345	2
Drip T8	68.5	59.7	51.37	1.6	Low	20012	3
Driptape T10	69	43.6	37.63	2.2	Low	20625	4
Sprinkler T4	81.7	23.8	21.31	4.6	Mod	21590	5
Driptape T12	68.7	26.4	23.55	3.5	Low	19302	6
Sprinkler T1	91.2	26.4	13.68	8	Mod	27591	7
Drip T7	58.4	45.4	41.22	1.7	Mod	15880	8
Sprinkler T3	79.9	6.9	6.14	15.6	Mod	19528	9
Drip T6	30.6	95.5	85.39	0.43	Mod	5876	10

Economic benefits were calculated using gross margins per hectare, based upon mean treatment yields, a mean price of $1200/tonne of fruit and base costs of $800 /tonne of fruit, and the additional irrigation total costs associated with each irrigation system.

The above process reveals that the optimum irrigation system for papaya production on krasnozem soil types in NQ could be chosen as T5, followed by T2,T8 and T10 treatments. The sprinkler system (T2) at full depletion of ASW has the advantage in yield which was consistently higher than for other treatments , however for large areas and with water limitations, the reduced irrigation costs and water usage of the driptape or drippers would probably give an advantage over sprinklers. For most growers however, the appeal of the increased yield and gross margins would probably make this system more popular without considering other factors. The higher gross margins of treatment T1 which was ranked low, illustrates the problem of encouraging the adoption of more efficient irrigation practices unless a yield benefit is also possible. The above results also need to be considered in relation to the high and well distributed annual rainfall in the Innisail area. For significantly drier areas or where there is a distinct dry season, single drippers would have to be pulse irrigated and it may be more feasible to use tape or sprinklers.

Papaya survey results (Richards 1995) established that 90% of growers were using micro-sprinklers, with typically one sprinkler watering up to 4 plants, thus the results from the trial confirm grower practices. The systems that gave the worst outcomes were single drippers at low irrigation rates (full depletion of ASW) or single sprinklers irrigated at either low or high rates. If single drippers are chosen (T5), then it is imperative to have very good irrigation scheduling to ensure that the soil water status is adequate in the very limited wetted area (0.19 sq.m) and due to the high water percolation rates under drip irrigation. It also should be remembered that yields are likely to be less than that obtained with T2. Single drip tape (t10) is less of a risk in this respect as the area wetted is 3 times larger and percolation rate reduced. Double drippers per tree (T8) irrigated at the low rate (full depletion of ASW) are less of a risk than T5, and possibly T2 (shared sprinklers) offers the least risk or potential loss were irrigation management and scheduling are not well practised or understood, and in a low rainfall environment.

The choice of one irrigation system over another will ultimately depend upon water supply, water quality, pumping capacity, climate and soil type. Coarse soils and soils of high clay content (low saturated hydraulic conductivity) will best be suited to the lower precipitation rates of sprinklers, whereas soils of medium to high conductivity (laterally and vertically) will better suited for emitter systems, to take advantage of higher infiltration rates and to reduce drainage through the root zone. If water quality is a limitation, then sprinklers may be favoured due to a reduced tendency to clog up; however, if salt is the limitation then foliage damage may result from sprinkler application. In the context of this trial, water quality and quantity were not limiting thus allowing the comparison of diverse systems simultaneously. The soil physical properties allowed water to be infiltrated effectively with all systems, and the flat land made runoff negligible

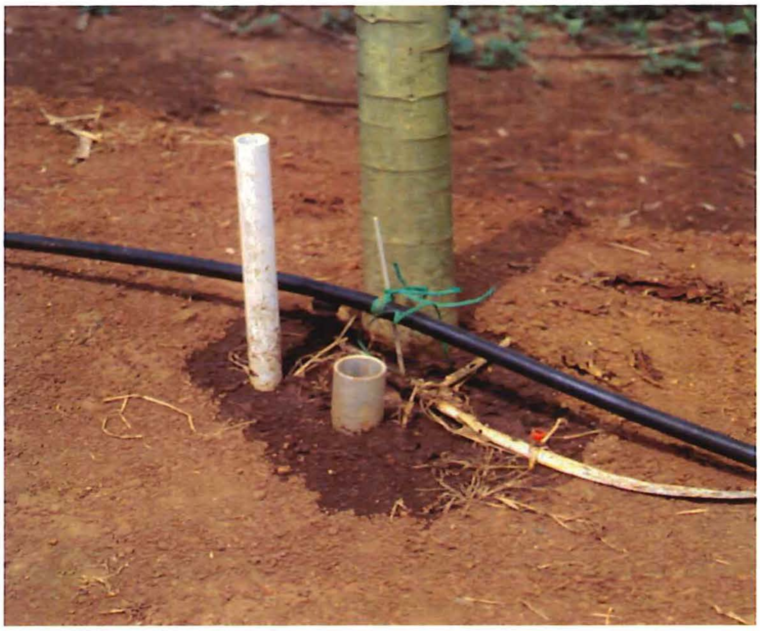
There are no other reported studies in the literature relating papaya production to wetted area or irrigation systems comparisons.

5.4 Conclusion

Rate of irrigation as determined by replacement of water at 50% and 100% depletion of PAWC, did affect papaya yield but not growth and fruit quality. The amount of water applied total was significant in yield responses, with an increase in yield up to 2500 litres per tree, which was found to be equivalent to a mean weekly application of 70 litres per tree. The optimum wetted area as achieved by different irrigation systems was found to be about 1 m^2 per plant, although highest yields were attained with shared sprinklers wetting 3.5 m^2 area per plant.
The best model to describe yield was found to be related to tree girth, rate of precipitation and soil water storage limits, which collectively described 90% of total yield variation. Tree size was well related, non-linearly to water applied per tree with little change in size beyond 1500 litres per tree. Crop coefficients at peak water use for sprinkler irrigated trees are 0.89 to 1.54.
Although many yield differences across treatments were only marginally significant, a comparison of agronomic, water usage, drainage and gross margins per hectare of all treatments revealed the best overall irrigation system to be shared sprinklers at the low irrigation rate, followed by double drippers and single drip tape. Differences due to irrigation rate were minimal partly due to the difficulty in imposing watering regimes over a shallow rooted crop. Drip tape responses were not fully evaluated due to the erratic yield obtained in alternative plots of two treatments. The single drippers at low rates were by far the least desirable system, and single drippers at high rates although rated 3rd overall, would seem to be more risky where irrigation scheduling is not accurate and timely. The large wetted area and water application rates of individual sprinklers per tree are wasteful of both dollars and water.

Photograph 2: **Treatments T11, T12: double drip tape.**

Photograph 3: Typical wetting pattern: Treatments T5, T6 , single dripper per tree . Note location of NMM tube and tensiometer.



Photograph 4: Typical wetting pattern: Treatments T7, T8, double drippers per tree.

Photograph 5: Typical wetting pattern: Treatments T1, T2, shared sprinkler per tree.

Photograph 6: Typical wetting pattern: Treatments T9,T10, single drip tape.

CHAPTER 6: STUDY OF PAPAYA ROOT SYSTEMS UNDER DIFFERENT IRRIGATION REGIMES.

6.1 INTRODUCTION

Root systems of perennial plants are seldom studied in any detail, and often overlooked completely, despite their obvious importance in plant function. Reasons for this include the high degree of difficulty in sampling a heterogeneous system, the length of time and the expense involved.

In the papaya irrigation trial discussed in Chapter 5, six different wetted areas were tested for papaya yield and growth responses. Significant yield and growth differences were established, and variations in profile water storage and usage detected. The aim of the current study was to assess to what extent irrigation practices had influenced root development, and how this information might be used in relation to fertiliser placement and water placement. The study was difficult to evaluate clearly due to the high rainfall in this area as mentioned previously.

6.2 METHODS AND MATERIALS

6.2.1 MOISTURE EXTRACTION STUDIES

In June 1996, 6 NMM tubes and 6 tensiometers each at 20 and 40 cm depth were installed in the papaya trial block at SJRS, in Mundoo soil. The soil was wet up to about 50 cm depth then daily readings taken over the next 8 days of all sensors, as shown in Figures 23 and 24.

Figure 23: Changes in volumetric water content following wetting up.

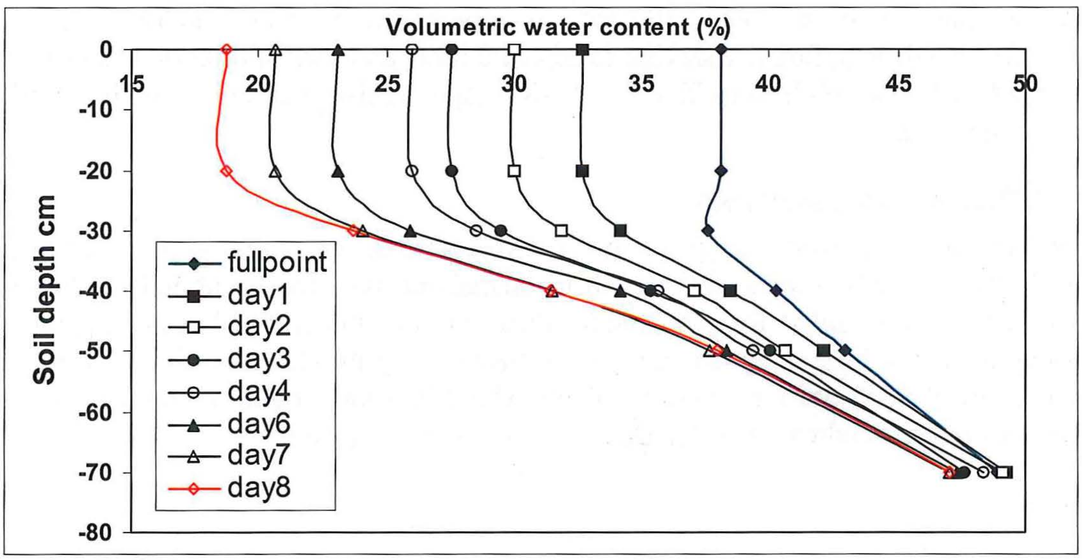
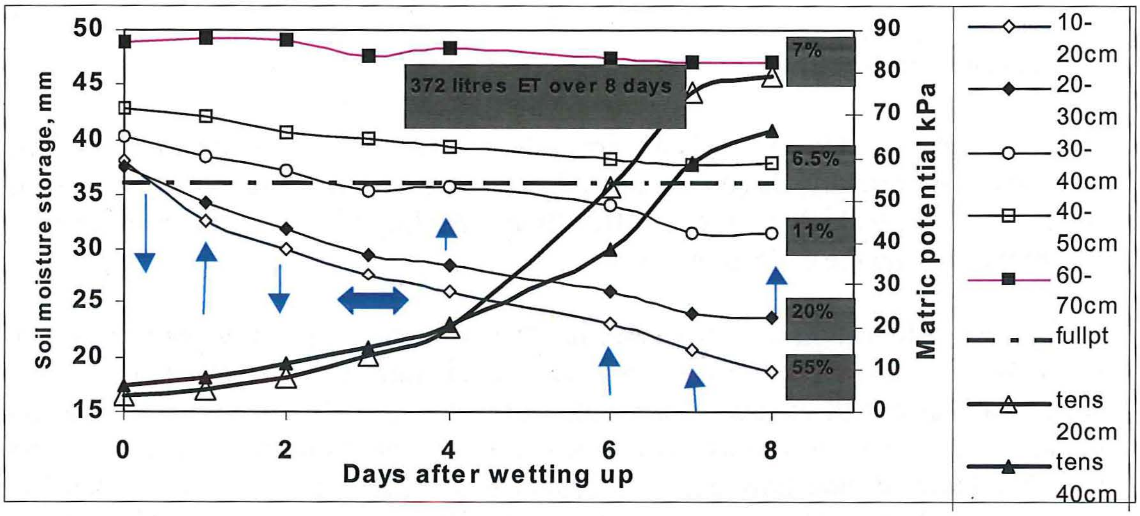


Figure 24: **Changes in stored soil moisture and matric potential with depth layers and time.**



In Figure 24 blue arrows indicate the flux of water based upon moisture potential gradients at 20 and 40 cm depth. By day 4, net flux is upwards to the surface indicating no drainage loss. Over 8 days 372 litres of water were used as Et, with 50% obtained in the top 0-20 cm zone. Changes in water storage show clearly the importance of the 0-20, 20-30 and 30-40 cm zones which changed by 55%, 20% and 11% respectively over 8 days. In contrast the 50-70 cm zones changed by less than 7%, indicating that most root water uptake is in the top 40 cm in this soil type.

6.2.2 Core sampling

In June 1997, trees from the Irrigation Trial (see Chapter 5) were sampled using a truck mounted hydraulic core sampler, of diameter 10 cm. For each tree sampled, 2 cores were collected about 50 cm from the trunk in both northerly and westerly directions, to a depth of 50 cm. Cores were extracted and cut into 10 cm lengths, with each sample of soil and roots collected into separate plastic bags. Samples were air dried for two days before dry sieving to separate roots and soil. A total of 3 trees were sampled each, for single sprinkler, single drip tape, double drip tape and single drip emitter per tree.

6.2.3 Destructive sampling

Data was collected from the Irrigation Trial tree destructive sampling (Chapter 5) in April 1997. Only two trees, one each from shared sprinkler treatment and single drip treatment were sampled for root system distribution. This entailed removing intact root systems, washing down and air drying, then cutting into 20 cm portions from the ground level. Such portions were then subdivided into lateral and taproot (including rhizome) parts, weighed, oven dried for moisture determination.

6.3 RESULTS AND DISCUSSION

The distribution of root densities (dry weight basis) obtained as means for each treatment is shown as Figure 25. These densities are points only, and not representative of the entire root zone; however, they are an indication of the weight of roots in a soil volume under different treatments. The data set is limited thus conclusions difficult to make. Despite this, it is apparent that the single dripper per plant generally, has lower root densities at all depths than the other treatments. The sprinkler irrigated plants seem to have a root concentration in the upper 30 cm soil, whereas the drip tape plants seem to have most of their roots in the 10 to 40 cm range. Overall, all treatments suggest that root distribution is largely concentrated in the top 40 cm of soil. This is further suggested in Figure 26, which shows on average, less than 20% of the total core sample root weights at 40 to 50 cm depth. Figure 26 shows individual tree mean data (2 cores/tree), and highlights the variability problems in this type of study. Taken together, the 10, 20 and 30 cm depths account for 50 to 90% of total root weights over the 4 treatments, and the addition of the 40 cm depth increases this to 70 to 100%.

Root size distribution with depth and treatments shows the dominance of smaller root sizes (<2 mm diameter) in papaya (Figure 27). This is more obvious for the trickle irrigated plants (dripper/driptape), whereas sprinkler irrigated plants tended to have larger numbers of roots in the 2-4, 4-6 and >6 mm class sizes. This is illustrated by reference to photographs 7 and 8 which illustrate a less fibrous, more open root architecture in comparison to photographs 9 and 10 (single dripper) which are more matted and fibrous.

The concentration of roots in the top 40 cm is shown in photographs 11, 12 and 13, and the tap roots extend no further than 120 cm. Measured radial spread of roots in the top 20 cm was about 1.5 m, thus effective ground area per mature plant is about 7 m^2.

Figure 25: Root density with depth for different irrigation treatments.

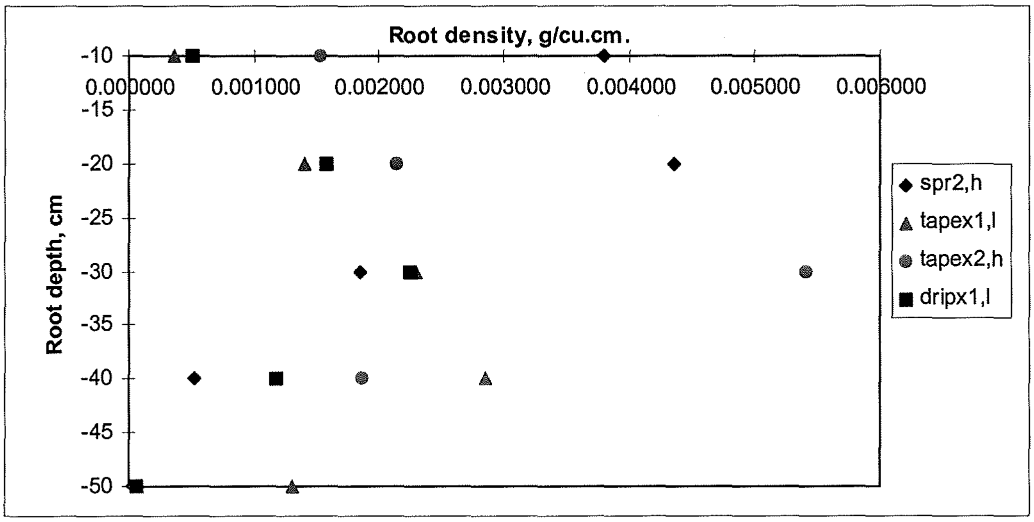


Figure 26: **The percentage root weight distribution in core samples over depth intervals to 50 cm depth, for different irrigation treatments.**

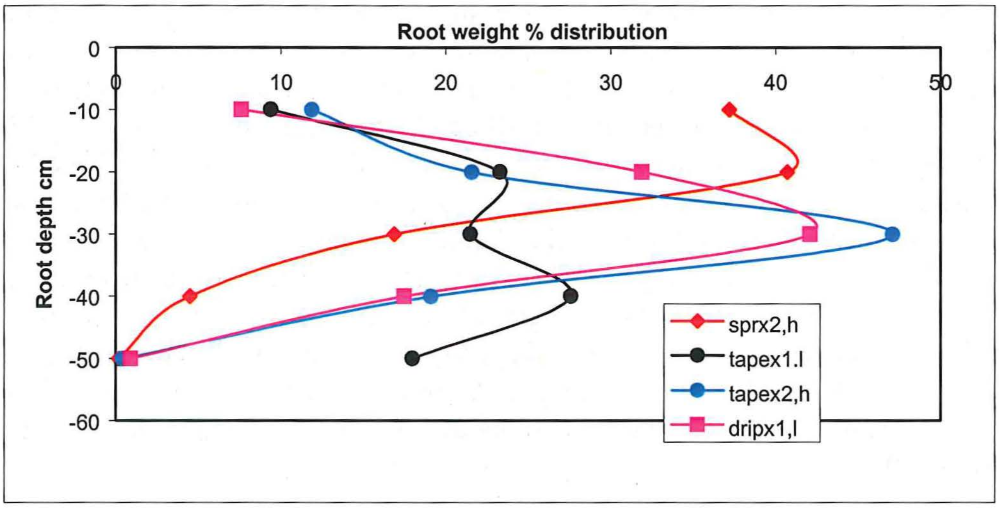


Figure 27: **The distribution of root numbers in core samples, for root sizes and depths, over different irrigation treatments.**

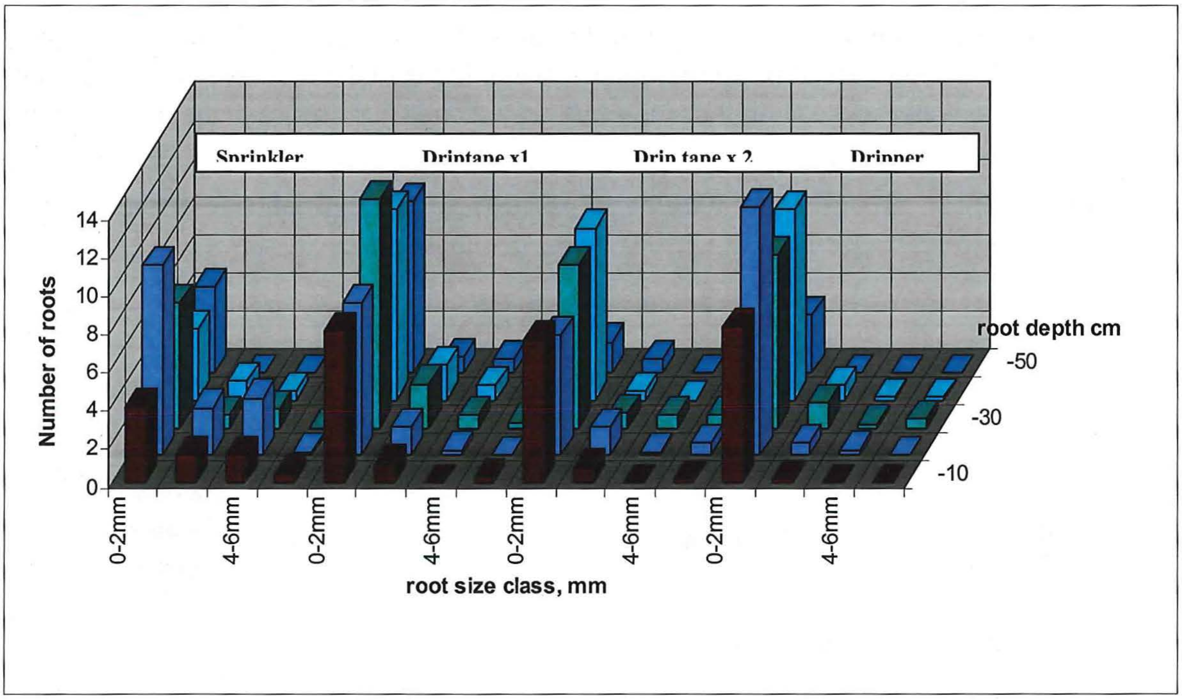
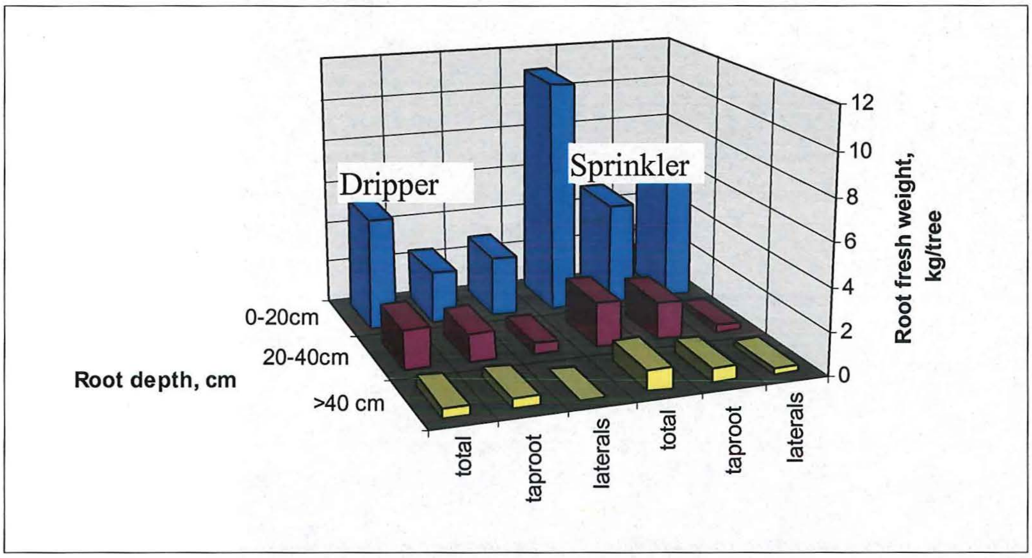
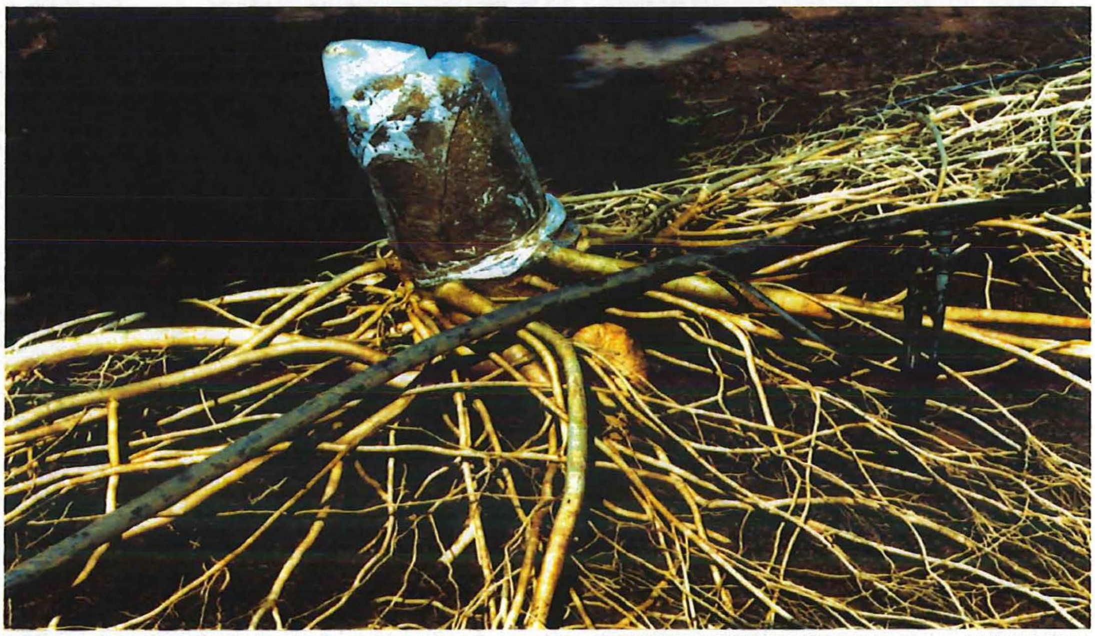


Figure 28: Depth distribution of root fresh weights for dripper and sprinkler irrigated plants.



Two diverse treatments in Figure 28 show the range of root system size as determined by irrigation treatments. The sprinkler irrigated trees produced much larger root mass, particularly in the top 20 cm of soil, thereafter with minimal differences in the two systems. Lateral roots dominated the top 20 cm layer of total root weight, but were appreciably smaller than the taproot components in lower layers. This is illustrated in photographs 12 and 13.

Photograph 7: Sprinkler irrigated root system.



Photograph 8: Sprinkler irrigated root system.

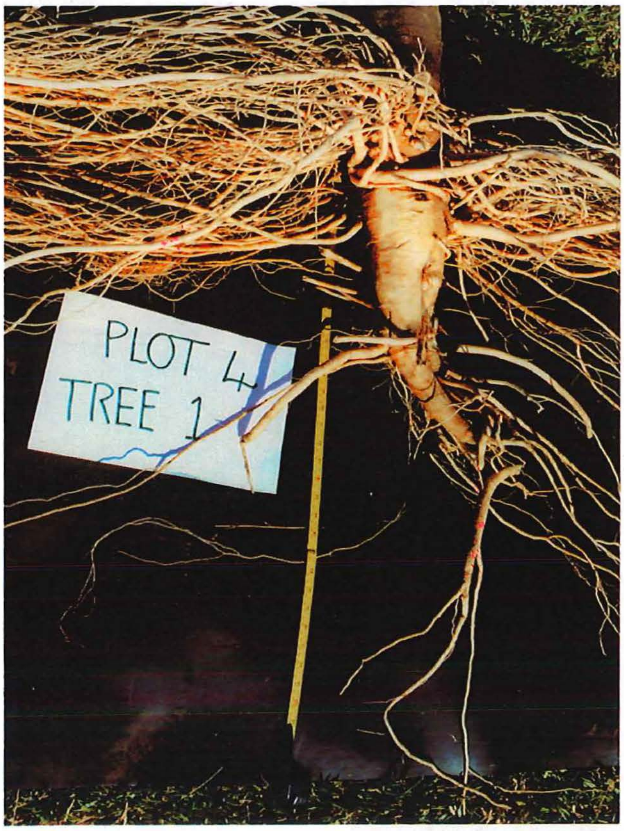
Photograph 9: Drip irrigated root system.

Photograph 10: **Drip irrigated root system.**

Photograph 11: **Sprinkler irrigated roots partially exposed.**

Photograph 12: **Sprinkler irrigated tree.**

Photograph 13: **Drip irrigated tree.**



CHAPTER 7: TOOLS FOR SUSTAINABLE SOIL WATER MANAGEMENT OF FARMING SYSTEMS - A CASE STUDY WITH PAPAYA.

(This paper was presented at the Irrigation Australia Association 1998 Conference in May.)

7.1 ABSTRACT

An integrated approach to establishing sustainable soil water management for crop production was developed, by using several tools or methods in sequence. These tools allowed the determination of soil properties vital to irrigation design and scheduling; the measurement of a specific crop response to diminishing water availability; the assessment of active zones of root uptake; the empirical study of soil behavior under different infiltration rates as imposed by drippers, drip tape and micro-sprinklers; the evaluation of agronomic and economic performance of alternative methods of water delivery; and a comparative analysis of irrigation systems and their ranking for a specific soil. The preliminary tool was the benchmarking of current practices, and the final tool the awareness, adoption and training implementation program, into the target audience.

7.2 INTRODUCTION

Studies on papaya irrigation commenced in March 1995, at South Johnstone Research Station (Innisfail) and this experience has lead to some generalisations or "Tools" that may be applied elsewhere. There is nothing new or revolutionary about the tools. What is rare however is to see complete investigations which examine soil and plant parameters, evaluate irrigation systems on plant performance, comment on soil suitability for emitters or sprinklers, and integrate these into soil water management guidelines for specific soil-crop combinations. The tools used and their applications are discussed.

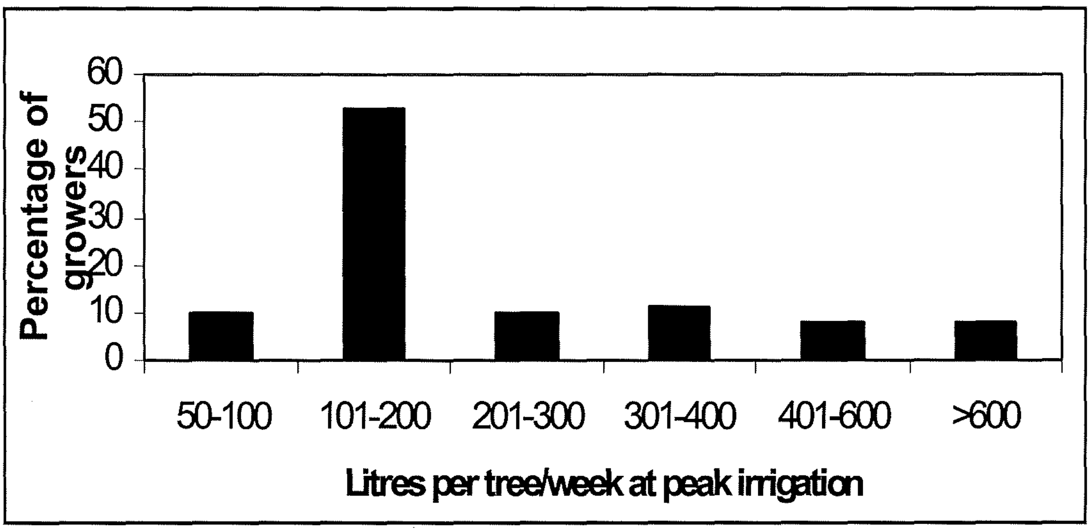
The mean annual rainfall for the South Johnstone Research Station is 3008 mm, and the mean evaporation 1585 mm. Deficits of rainfall over evaporation most commonly occur between August and November. Mean monthly minimum temperatures are least at 15 degrees C in June/July and mean monthly maximum temperatures are highest in December/January with32.5 degrees C.

7.3 RESULTS AND DISCUSSION

7.3.1 TOOL 1: BENCHMARKING OF IRRIGATION PRACTICES

A survey of grower irrigation practices was completed in 1995 by Richards *et al.*, for major growing areas in North Queensland (NQ). In NQ 90% of growers used under tree micro-sprinklers to deliver water, commonly sharing one sprinkler over 4 trees, and all growers surveyed used irrigation. The most common irrigation rate was about 100-200 litres per tree per week during peak periods, with the maximum over 600 litres per tree per week (Figure 29). Irrigation was carried out through the year and stopped only during intense, prolonged raining periods. In NQ the average maximum irrigation period was 18 hours per week, delivering about 30mm per tree per week.

Figure 29: Irrigation output distribution of North Queensland papaya farms.



All irrigators scheduled by assessing soil moisture as indicated by soil colour and based upon previous rainfall. A number of growers (20%) had used or still use tensiometers, but their maintenance and interpretation presents a common problem. Only one grower had access to a Neutron Moisture Meter and no Capacitance probes were in use. The concepts of available soil water, refill and full points in the soil, papaya water use under different conditions and stages of growth, have not been investigated in any region, thus previous practices and experiences tend to dominate growers attitudes to irrigation management. Most growers expressed a concern of not knowing whether they were irrigating correctly; viz. whether they were providing too little or too much water and at what stages should water be applied.

7.3.2 Tool 2: Verifying the Active Uptake Root Zone

In designing irrigation systems and in scheduling irrigation it is essential to know the design rooting depth for the crop to be grown, in order to reduce drainage losses and supply adequate amounts of water per plant. A Mundoo series Krasnozem soil (Murtha and Smith 1994) was selected for study (Table 14) due to its common usage for papaya production in the area.

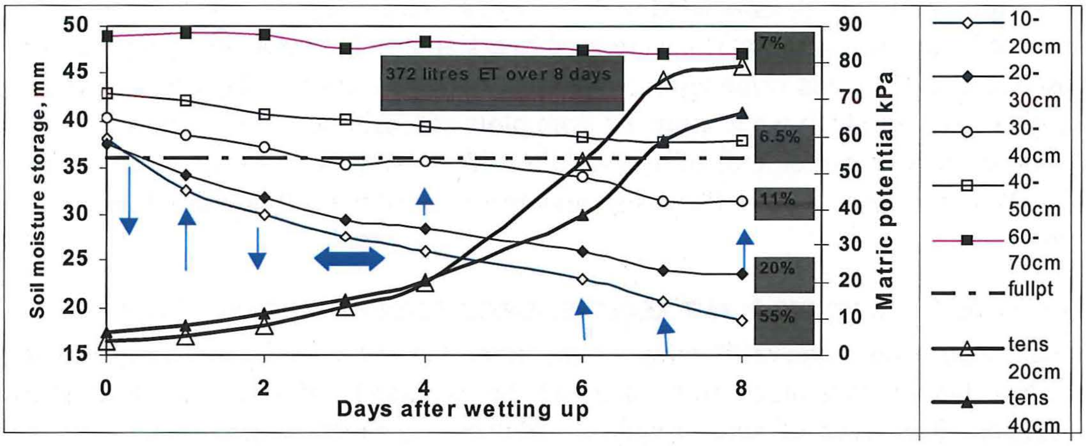
Table 14: Physical properties of Mundoo soil type studied for papaya irrigation.

	Clay (%)	Silt (%)	Sand (%)	Bulk density g/cm^3
Mundoo 0-20cm	68	17	15	1.26
20-40cm	76	15	10	1.27
40-60cm	77	13	10	1.33
60-80cm	77	12	10	1.33

In June 1996, daily measurements of changes in soil volumetric water content, θ_v from plant plots watered to full point, then allowed to dry out the soil, were used to calculate soil moisture storage changes with different root zone depths (Figure 30).

Changes in the 20 cm zone were rapid with moisture change of 55% over 8 days. The 30 and 40 cm zones also recorded substantial changes in storage, but the changes at 50 and 70 cm depth were minor. Changes in storage reflect plant water usage, soil evaporative losses and drainage. The 50 and 70 cm zones did not show substantial increases or decreases in storage water, even after 8 days, suggesting very little root activity in these zones. The most active region for root uptake in this soil appears to be the top 40 cm of soil.

Figure 30: Changes in stored soil moisture in different soil zones, following wetting up and drying.



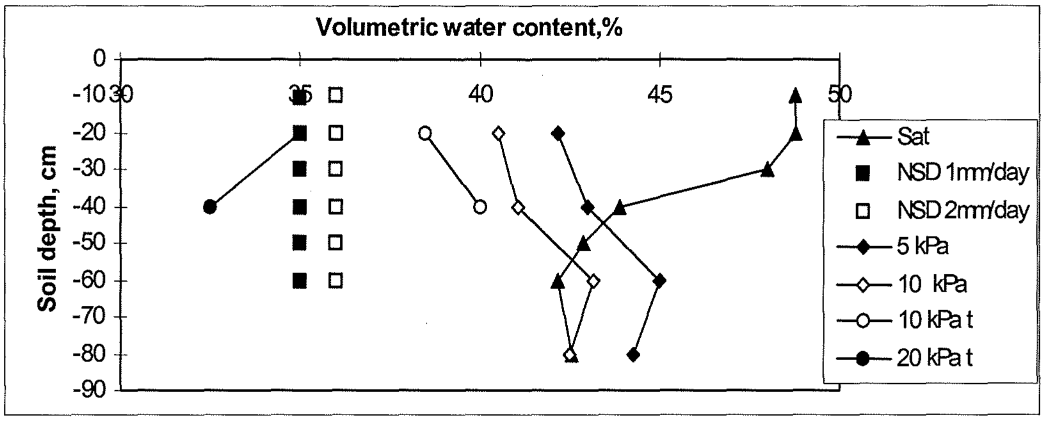
Arrows in Figure 30. indicate the water flux direction based on moisture potential differences at 20 and 40 cm depth. After 3 days the flux is dominantly upwards, suggesting moisture changes are due to evapotranspiration. During the period of 8 days a total of 480 litres of water per tree was used with 55% in the top 20 cm zone.

7.3.3 Tool 3: Checking the soil: finding the full point

Field drainage studies and soil matric potential data, from both tensiometers and soil cores equilibrated with suction table apparatus determined the full point for the Mundoo soil. Field assessment of non-significant drainage rates (NSD), cumulative drainage and storage limits were completed based upon the procedure as used by Leuning and Talsma (1979). After complete wetting and cessation of infiltration, NMM (neutron moisture meter) readings commenced to record saturation moisture profiles down to 150 cm. Readings were taken at various intervals over the next 30 days of both the NMM and tensiometers.

Changes in stored moisture, S, in the top 80cm interval were described by the hyperbolic function (R^2=0.98) S= 261.6 +(94.03/(1+0.29t)). This function was used to calculate non -significant drainage rates (NSD) at 1 or 2 mm/day. Bulk density cores were collected at 20, 40,60 and 80 cm depths for determination of soil moisture retention at –5 and –10 kPa. Loose samples for PWP were also collected

Figure 31: Various moisture retention's following wetting up of Mundoo soil.



The various values of θ_v associated with NSD rates, tensiometer retentions and laboratory retentions (Figure 31), were used to assign a full point level. Full point was chosen at 36% θ_v as this value lay between the two NSD rates and the tensiometer retentitivity data (which were extracted from plots of tensiometer matric potential vs θ_v). Laboratory measurements of μ_s at -5 kPa and at -10 kPa over estimated the full point. Tensiometer μ_s at -33 kPa was an underestimate of the full point (data not shown).

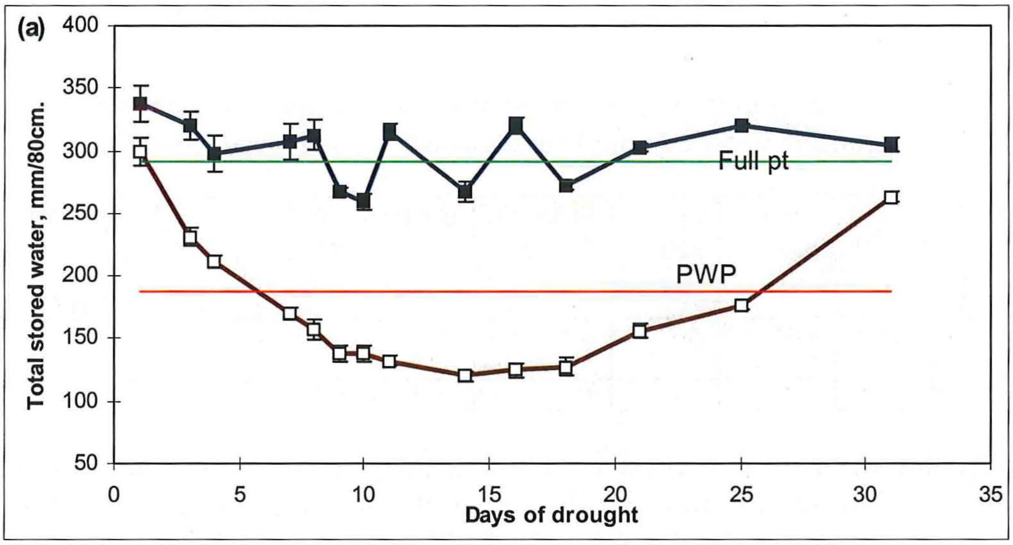
7.3.4 TOOL 4: CHECKING PLANT REQUIREMENTS: FINDING THE REFILL POINT

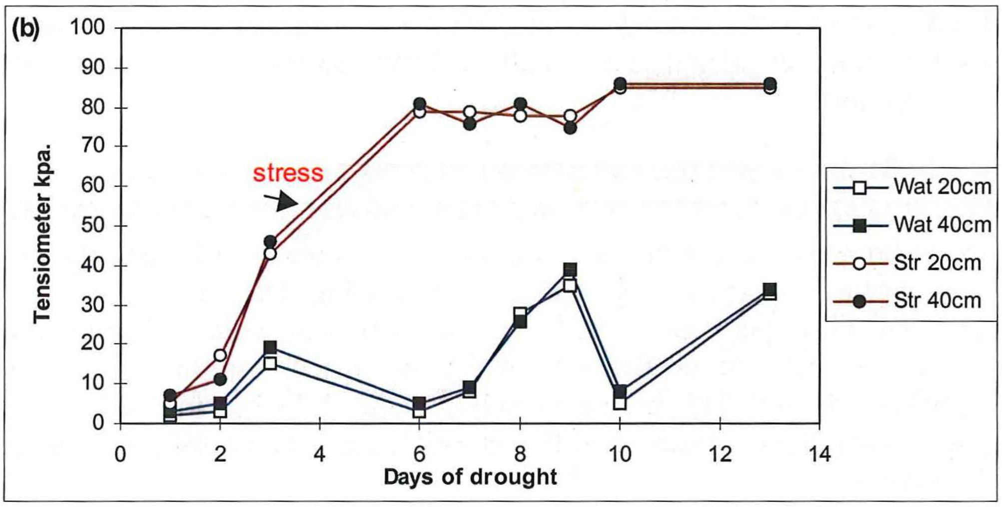
The determination of the refill point is a function of crop type, crop stage and climate; the issue being: how much soil water can be extracted before plants show stress symptoms? This type of study requires simultaneous measurement of the soil and plant moisture status, ideally over different crop stages and seasons. For the Mundoo clay soil, measurements of θ_v for both watered and droughted papaya plantswere determined using a NMM at 20, 30, 40, 50, 60, 70 and 80 cm depths and the calibration equations previously developed. Resultant stored soil moisture for 0-40cm and 40-80cm depths ranges and means were calculated. Soil moisture potential was measured using a Soil Spec system and means of at least 4 tensiometers per site and depth (20 and 40 cm) were taken at selected times. The studies were conducted from August to December 1996.

Measurements with a Pressure Bomb (Scholander et al. 1965) commenced in June 1996. It became rapidly apparent that papaya leaves were not suited to this technique as it was difficult and unreliable to differentiate sap and water exudation from petioles or veins. This is a problem with a number of other crops including banana and mango. Consequently this method to measure plant water stress was abandoned, and two other techniques evaluated. The first was RWC (relative water content) (Barrs 1968), and this too proved less than satisfactory. The last technique investigated was the simplest of all; the measurement of fruit volume changes, and the results of assessing onset of water stress using this method are discussed herein.

For fruit measurements, 10 papaya plants each was selected from watered and stressed treatments, and the length and diameter of marked fruits on each of 10 trees was measured regularly using calipers. Large differences in stored soil water S, of the watered and stressed papaya plants were obtained (Figure 32 (a),). Very low values of S were attained in the Krasnozem after 7 days of drought in December (Figure 32 (a)) and these S values reached well below the PWP lower storage, and may relate to expanded neutron scattering anomalies in dry soils. Changes in soil moisture potential and fruit volume are also shown, as Figures 32 (b) and (c).

Figure 32: **Changes in (a) total soil water S mm (0-80cm), (b) soil matric potential and (c) fruit volumes, for watered plants (wat) and stressed plants (str) following drought. Bars indicate s.e. values.**





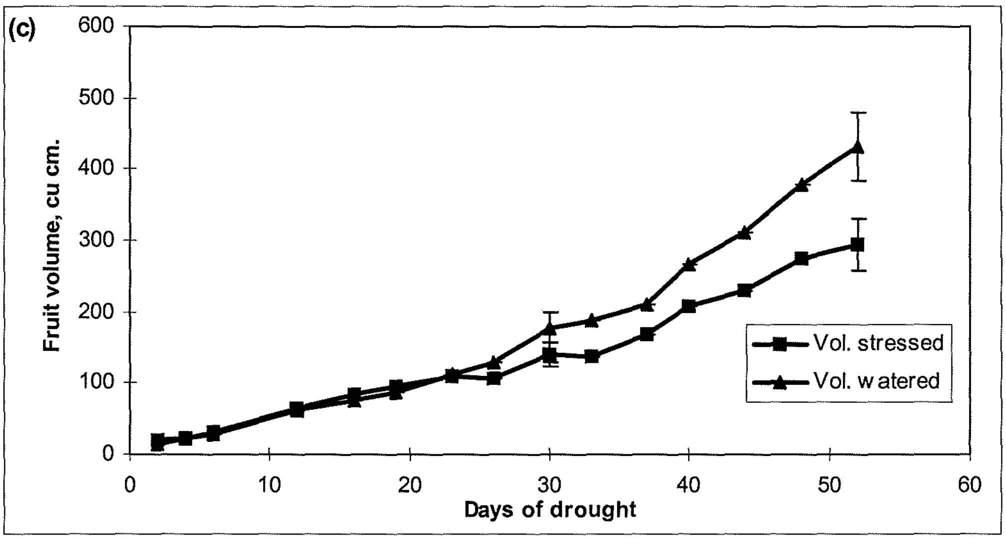


Table 15: Derivation of PAWC (plant available water capacity), and AWC (available water capacity) based upon NSD and tensiometer data.

Depth range	Full pt mm	PWP mm	μ_s kPa full pt	Refill pt. Mm	μ_s kPa	AWC , mm	PAWC mm	PAWC, % depletion of AWC
0-40 cm	144(36.0 %)	89(22.5 %)	-15	108 (27%)	-60	74	36	
0-80 cm	288	185		217		148	71	48

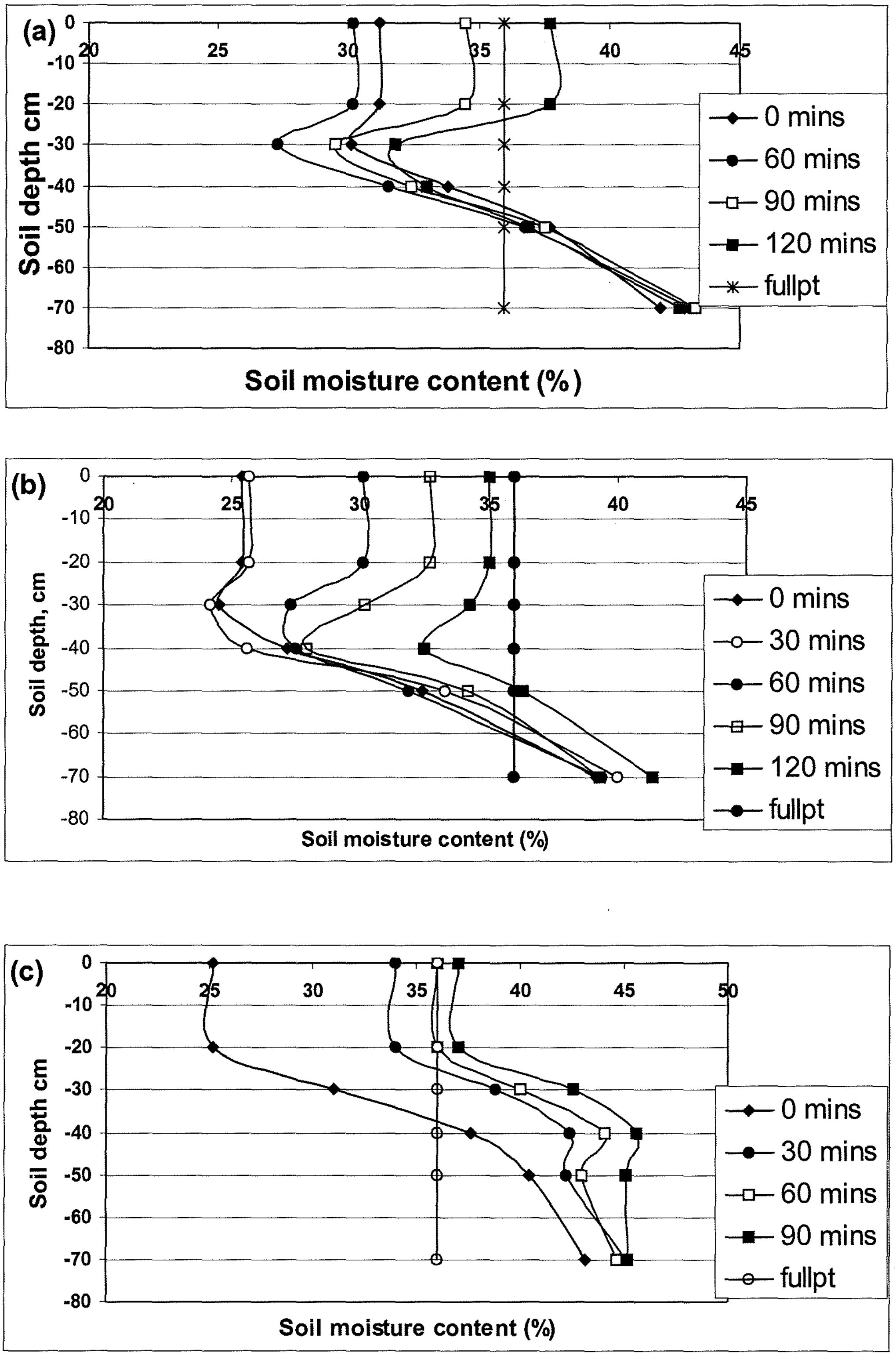
The refill point was derived by considering soil matric potential changes and changes in fruit volumes, in relation to decreasing soil water contents, which gave PAWC much lower than the calculated AWC. The PAWC based upon 50% depletion of AWC gave similar PAWC for the Mundoo clay, in comparison with refill point derived PAWC. The PAWC was calculated at 0.09 mm water/ mm soil, and PAWC based upon laboratory retention data at -10 kPa and PWP grossly exaggerated PAWC at 0.184 mm/mm soil.

7.3.5 Tool 5: Study of emitter and sprinkler flow characteristics, wetting patterns, Precipitation rates, and wetting front advance.

Knowledge of how fast water enters the soil and moves through it beyond the root zone is essential for irrigation management decision making. The gross precipitation rate of the outlet (Litres per hour/ wetted area) has to be matched to soil infiltration rates, the saturated hydraulic conductivity of the soil in root zone layers, and the storage capacity of the soil. This is an extremely complex 3 dimensional soil physics problem, for which field studies on different soil types can be used to provide empirical solutions.

Using the Mundoo soil, micro-sprinklers, drip-tape and drippers were studied for emission characteristics and the reactions of soil to wetting. The increase in wetted area for emitters leveled off at about 1.5 hours of irrigation, at which time wetted areas per plant were 1.2 m^2 , 0.7 m^2 and 0.2 m^2 , for respectively double drip tape, single drip tape and single drippers. Measured gross precipitation rates were respectively, 6mm/hr, 18 mm/hr and 38mm/hr for sprinklers, drip-tape and button drippers.

Figure 33: **The variation in Mundoo soil moisture content with time for (a) single sprinkler, (b) single drip tape and (c) single dripper.**



From Figure 33(c) the rapid wetting front advance through the root zone (0-40cm) is apparent with an 8L/hr button dripper. Some time after about 30 minutes of irrigation, the soil is close to or exceeding full point. The sub-root zone was very wet prior to irrigation indicating lack of water use in this zone from both irrigation and rain application. Maximum irrigation run time in this soil for this capacity dripper was set at 30 minutes for papaya.

Single drip line tape (Figure 33 (b), 30cm spacing 2.5L/hr/emitter) illustrates a totally different wetting pattern of the soil before and during irrigation. To wet the soil to near full point took 2 hours, at which stage the subsoil at 50cm depth was at full point. The wetting front had apparently had a mean rate of advance of 25 cm/hour. To allow for redistribution and to avoid subsoil drainage, the maximum run time for papaya in this soil was set at 1.5 hours.

Micro-sprinklers (Figure 33 (a) 40L/hr), showed the slowest rate of wetting of all three outlets. After 2 hours, there was only a slight increase in moisture content at 40 cm depth and the mean rate of advance appears to be about 12.5 cm/hour. To allow for redistribution effects the maximum run for this type of sprinkler on this soil was set at 3 hours for papaya irrigation.

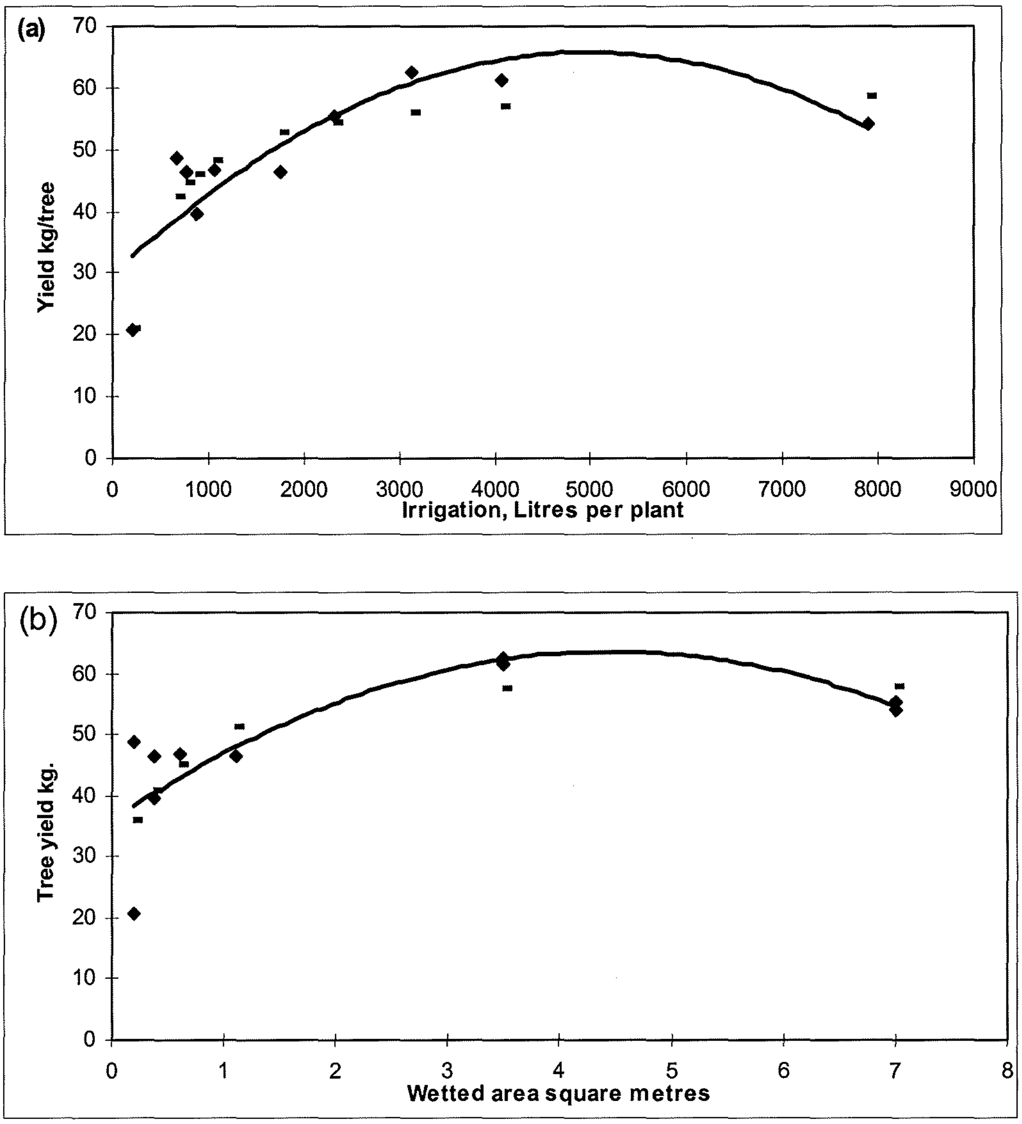
7.3.6 Tool 6: Determination of agronomic and economic performance under different emitter and sprinklers (treatments)

A field trial consisting of 12 irrigation treatments replicated twice, and with 16 plants per replicate was established in October 1995 and completed in March 1997. Treatments consisted of single and double drip-tape, single or double button drippers, and single or shared micro-sprinklers.

Rate of irrigation as determined by replacement of water at 50% and 100% depletion of PAWC, did affect papaya yield but not growth and fruit quality. The amount of water applied total was significant in yield responses, with an increase in yield (non linear Figure 34 (a)) up to 2500 litres per tree, which was found to be equivalent to a mean weekly application of 70 litres per tree. The optimum wetted area as achieved by different irrigation systems was found to be about 1 m^2 per plant, although highest yields were attained with shared sprinklers wetting 3.5 m^2 area per plant. The relation ship of yield and wetted area per plant was also non linear (Figure 34 (b)).

These results compare well with commercial yield results obtained in NQ, and optimum water rates lower at 2600 litres/tree or 70 litres/tree/week (Figure 33 (a)). For shared sprinklers the actual maximum weekly water application was 220L/tree in November, and for double drippers 73L/tree and for single drip-tape 76 L/tree.

Figure 34: **Papaya yield kg/tree, in response to (a) litres per tree applied and (b) the effect of wetted area per plant. Non-linear regression values are indicated.**



In order to assess the economic sustainability of treatments evaluated in this trial, costs of installing the systems, pumping and water purchases, assuming water is sourced from an irrigation area, were calculated and compared. All costs are on a per hectare basis, and installation costs allow for different emitter or sprinkler, lateral, mains, sub mains, filtration and pump costs. Pumping costs were estimated at \$100/ML and water costs at \$22/ML.

Table 16: Comparisons of irrigation installation and operating costs (AUD) per hectare, for the 12 different systems evaluated.

System	ML/ha* to apply	Water cost $	Installation costs $	Pumping costs $	Total costs$ / ha	Total costs$/ 10 ha
sprinkler shared T1	8	176	7963	800	8909	89,090
sprinkler shared T2	6.2	136	7963	620	8719	87,190
sprinkler x1 T3	15.6	343	10529	1560	12432	124,320
sprinkler x1 T4	4.6	101	10529	460	11090	110,090
dripper x 1 T5	1.3	29	6311	130	6470	64,700
dripper x1 T6	0.43	10	6311	43	6364	63,640
dripper x2 T7	1.7	37	7273	170	7480	74,800
dripper x2 T8	1.6	35	7273	160	7468	74,680
drip tape x1 T9	2.4	53	6107	240	6400	64,000
drip tape x1 T10	2.2	48	6107	220	6375	63,750
drip tape x2 T11	4.6	101	7751	460	8312	83,120
drip tape x2 T12	3.5	77	7751	350	8178	81,780

The cost advantages of dripper and drip tape treatments is apparent from Table 16 as is the high cost of sprinkler designs of treatments T3 and T4. As expected, installation costs are by far the largest cost, although operational costs for T3 are comparatively high.

7.3.7 TOOL 7: COMPARATIVE ANALYSIS OF IRRIGATION TREATMENTS AND PLANT RESPONSES

Using agronomic and economic results from the irrigation trial (Tool 4), and a study of water usage, a whole treatment evaluation was determined as in Table 17. For each factor assessed a score out of 10 or 20 was determined, with the highest score being the most desirable level.

Economic benefits were calculated using gross margins per hectare, based upon mean treatment yields, a mean price of $1200/tonne of fruit and base costs of $800 /tonne of fruit, and the additional irrigation total costs associated with each irrigation system.

The above process reveals that the optimum irrigation system for papaya production in NQ on Mundoo type soils, could be chosen as micro-sprinklers, followed by double drippers per plant and single drip-tape. Drip tape responses were not fully evaluated due to the erratic yield obtained in alternative plots of two treatments. The single drippers at low rates were by far the least desirable system, and single drippers at high rates although rated 3rd overall, would seem to be more risky where irrigation scheduling is not accurate and timely. The large wetted area and water application rates of individual sprinklers per tree are wasteful of both dollars and water.

Table 17: The assessment of irrigation systems based upon agronomic, environmental and economic performance indices.

System	Yield t/ha	Yield g/ L irrig	$return /KL irrig	Water applied ML/ha	Drainage potential >40cm	Gross margins $/ha	Overall ranking
Drip T5	71.9	72.1	66.37	1.3	Mod	22290	1
Sprinkler T2	92.7	19.9	17.93	6.2	Low	28345	2
Drip T8	68.5	59.7	51.37	1.6	Low	20012	3
Driptape T10	69	43.6	37.63	2.2	Low	20625	4
Sprinkler T4	81.7	23.8	21.31	4.6	Mod	21590	5
Driptape T12	68.7	26.4	23.55	3.5	Low	19302	6
Sprinkler T1	91.2	26.4	13.68	8	Mod	27591	7
Drip T7	58.4	45.4	41.22	1.7	Mod	15880	8
Sprinkler T3	79.9	6.9	6.14	15.6	Mod	19528	9
Drip T6	30.6	95.5	85.39	0.43	Mod	5876	10

7.3.8 TOOL 8: EMBARK ON CRUSADE "AWARENESS, TRAINING, ADOPTION OF RESULTS"

The last point, the transfer to and subsequent adoption by the irrigation community, requires its particular set of tools and tricks of trade. It goes without saying that using the first 7 tools discussed herein will only result in the delineation of correct guidelines for soil water management. The eighth step is essential in order to achieve sustainable soil water usage amongst irrigators, and will require an iterative process of informing /training /adoption and benchmarking.

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CHAPTER 8: GENERAL INTRODUCTION

8.1 THE PROBLEM: HOW MUCH NITROGEN AND POTASSIUM DO PAPAYA PLANTS NEED TO OPTIMISE YIELD, FRUIT QUALITY AND SUSTAINABILITY OF PRODUCTION.

Previously, no fertiliser response trials have been established in Australia for papaya, and current recommendations are based upon limited survey work in southeast Queensland (Robinson 1986). These recommendations will often be inappropriate for north Queensland soils and climates and for other growing regions. Papaya plants are fast growing, producing fruit continuously from 7 month onwards for up to 2 years typically, before replanting. The nutrient demand thus is expected to be high and under-fertilising may result in yield and quality decline. Of concern also to growers is the issue of over-fertilising, with possible excessive vegetative growth, quality deterioration and leaching of nutrients.

In this context the papaya industry commissioned trials to validate existing grower practices and to define papaya nutrient requirements in Queensland. This did not extend to consideration of fertiliser delivery and placement options i.e. fertigation vs broadcast vs banded applications. For simplification these studies focussed on broadcast applications of fertilisers adjacent to plants.

8.2 LITERATURE REVIEW

A great deal of nutrition research on papaya has been conducted overseas, particularly in Hawaii. This may be subdivided for summary into the following sections:

Critical or adequate concentrations

Bowen (1992) derived critical concentrations of N 1.28%, P 0.185%, K 2.78%, Ca 0.22% and Mg 0.58% in papaya petioles. Awada and Long (1971a) in Hawaii, established critical N in petioles at 1.28%, equivalent to 800 mg/kg of nitrate N, and critical K at 2.75% (Awada and Long 1971b). The critical P of 0.21% in petioles was established in Hawaii by Awada and Long (1969). Reddy *et al.* (1988) established adequate concentrations in petioles of N 1.23%, P 0.28%, and K 3.44%. Optimal soil pH range was measured at 5.5 to 6.7 for Hawaii by Awada *et al.*(1975). In Australia, Robinson (1986) reported adequate N as 1.3 -2.5%, P 0.2-0.4%, K 3-6%, Ca 1-2.5% and Mg 0.5 - 1.5%.

Fruit quality responses

No effects of varying N, P or K on fruit TSS were measured by Reddy *et al.* (1988), but Awada and Suchisa (1970) found at zero N application, fruit size was smaller with no difference in TSS, and that both fruit size and TSS increased from zero to medium K rates of application. Purohit (1977) established a significant effect of increasing K application on fruit TSS from 7.6% to 11.9% at 415 g/plant/year.

Yield and growth responses

Purohit (1977) reported highest yields at 161 tonnes/ha over 18 months using 250g N, 110 g P and 415 g K per tree per year. Awada and Long (1971a) reported no differences in tree size across a range of N applications, however yields ranged from 24 kg/tree/year at low N to 96 kg/tree/year at high N (1000g/year). Awada and Long

(1971b) also reported at critical K concentrations, yield was 91kg/tree/year achieved by applying 630g K /tree/year. Reddy *et al.* (1988) established significant differences of N and P on tree growth but not due to K. The highest yields reported were 155 tonnes/ha over 24 months using 250 g N, 150 g P and 225 g K per tree per year.

Index tissue

Awada (1969) selected petioles over leaf blades as the index tissue on the basis of superior yield relationships. He chose the leaf subtending the most recently opened flower as the sampling position, and reported that total N was more useful than nitrate N in deriving nutrient relationships. Reddy *et al.* (1988) obtained best relationships of petiole concentrations and yield by using the 6^{th} petiole from the apex, which corresponds to Awada's flower position. Marchal (1986) in Cameroon selected petioles 17 to 20 which corresponded to mature petioles subtending recently opened flowers. He also established that N and P in blades was higher and K lower than in petioles, and that leaf blades were more sensitive to N changes and less sensitive to P, K, Ca, Mg changes than were petioles.

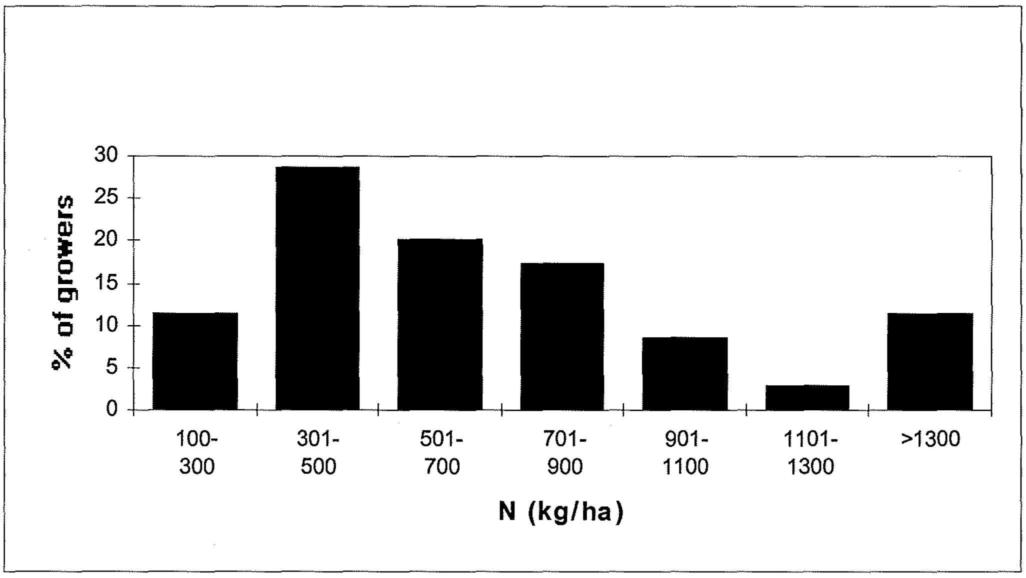
Nutrient removal

Awada and Suchisa (1970) found that significant amounts of nutrients were removed in fruits, as N 132g, P 18 g, K 177 g, Ca 42 g, and Mg 19 g per tree per year. Reddy and Kohli (1989) established N application induced early flowering and increased total biomass compared with unfertilised plants. Total plant biomass at 480 days after planting was 2.34 kg dry weight /tree in order of contribution as stem, fruit, roots then leaves. The root percentage of total biomass was 12.7%.

8.3 BENCH-MARKING OF QUEENSLAND PAPAYA INDUSTRY NUTRIENT MANAGEMENT PRACTICES

A survey of grower nutrient management practices was completed in 1995 by Richards *et al.* (1995) for major growing areas in north, central and southeast Queensland. Figure 1 shows the variability in nitrogen fertiliser management practices, with high levels of N being applied by more than 60% of growers. The distribution of nitrogen fertiliser is mainly after fruiting has commenced (stage 3), with little (about 10%) applied before flowering (pre-plant and stage 1). The levels generally applied (500+ Kg/ha N) equate to 20 bags urea per hectare over the 2 year cycle which is a very high application rate for any crop.

Figure 1. The distribution of nitrogen application rates on north Queensland papaya farms.



Phosphorus (P) fertilisers are also generally applied at higher rates in NQ, as shown in Figure 2. The high P absorption and fixation in many soils in the region has led farmers in this direction. More than 75% of growers apply 300kg/ha or greater of P fertiliser, which equates to about 30 bags per hectare of triple superphosphate. Almost half of this P fertiliser is applied during the fruiting and harvesting stage.

Figure 2. The distribution of phosphorus application rates on north Queensland papaya farms

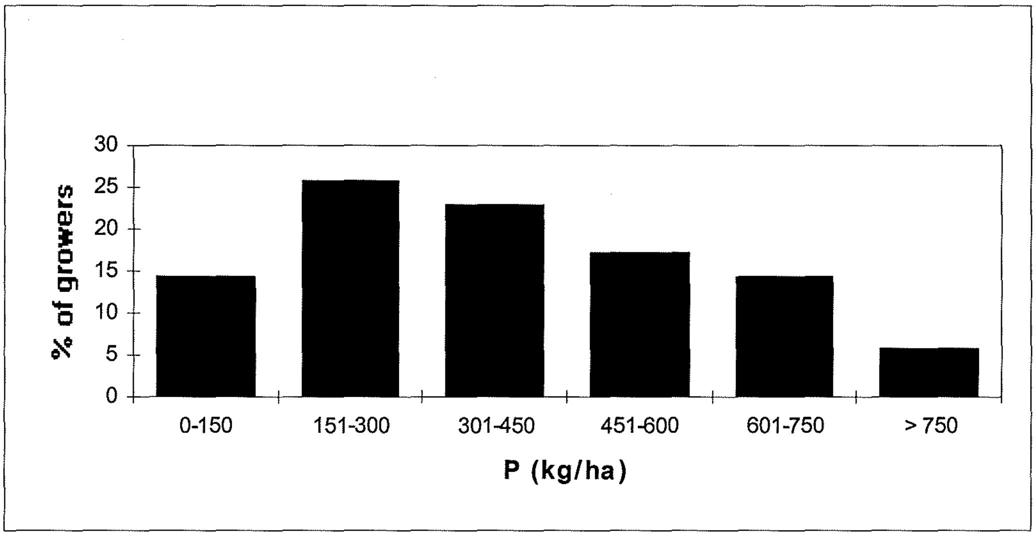
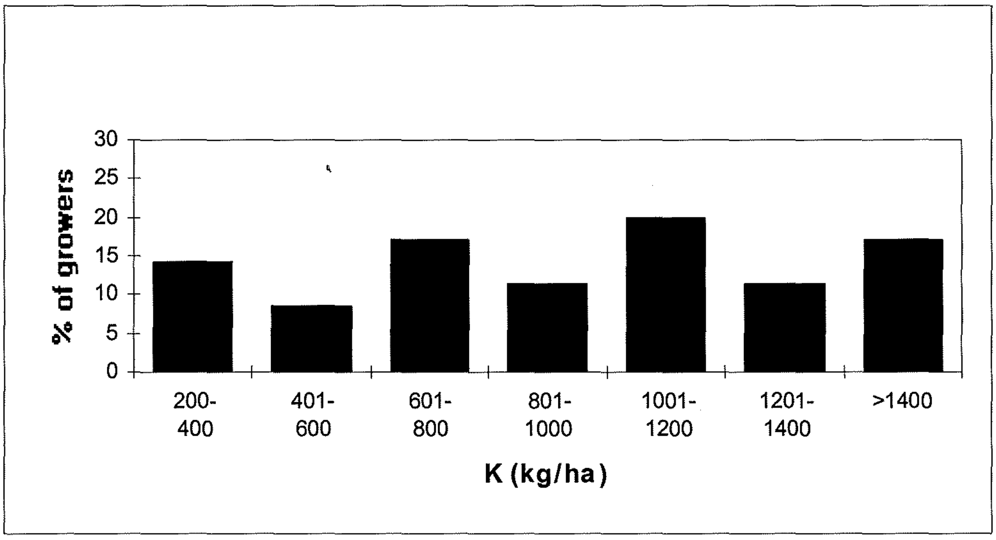


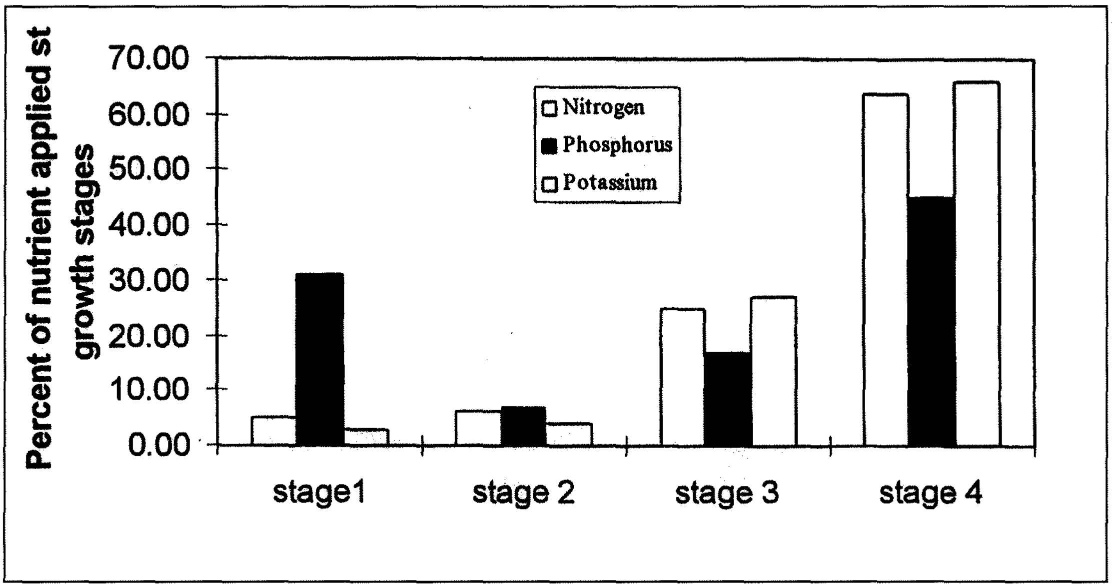
Figure 3 illustrates the distribution of potassium (K) fertilisers on NQ papaya farms. The rates of distribution are fairly evenly distributed over the range 200 to 1400 kg/ha of K. This range approximates to the equivalent of 8 to 56 bags per hectare of muriate of potash per two year period.

Figure 3. The distribution of potassium application rates on north Queensland papaya farms



The distribution of N, P and K fertilisers in relation to growth and production stages of papaya in NQ, are indicated in Figure 4. Both nitrogen and potassium illustrate rapidly increasing levels of application in the fruiting stages 3 and 4. Phosphorus is more uniformly distributed, but shows a marked drop in the vegetative stage (stage 2), and additional applications after fruiting has commenced.

Figure 4. Application of N(□ on left), P and K(□ on right) fertilisers in relation to papaya development and fruiting stages. The whole cycle is for a two year period from planting to last harvest.



Stages of development: 1 = pre-plant
2 = vegetative growth
3 = flowering/pre-harvest
4 = flowering/harvest.

The mean application of calcium was 1.85 tonnes per hectare, which is equivalent to 5.5 tonnes per hectare of applied limestone. Such a high level of application is a result of the nature of soils used (high buffering capacity) and the acidifying effects of N and P applied fertilisers. Magnesium as dolomite is applied at equivalent rates of about 4.9 tonnes per hectare. Sulphur as found in other fertilisers, particularly superphosphate is also applied at high rates of about 180 kg/ha of sulphur.

Most farmers in NQ apply B and Zn micronutrients with fairly diverse rates and timings, usually as bi-monthly irrigation injections or as foliar sprays. Other micronutrients such as Fe, Mn and Cu are usually applied once or twice per year.

In central and southern Queensland only very limited data were collected on fertiliser practices. Lime and dolomite are not routinely applied and when they are, at low rates of less than 2 tonnes per hectare.Nitrogen, phosphorus and potassium fertilisers are used more sparingly generally than in NQ, and fertigation is not commonly used in south and central Queensland. In contrast, fertigation is used by about 50% of growers in NQ on a regular (fortnightly or monthly) basis. The reduced rainfall, more fertile soils, colder climates and reduced availability of irrigation water in SEQ and CQ relates to reduced nutrient requirements in these regions, than that required in NQ.

A large number of papaya petiole and soil analyses results were collated using data collected from growers and from DPI officers, over the last 6 years (Tables 1 and 2).

Table 1. Means and coefficients of variation (CV%) for petiole nutrient concentration obtained from NQ, CQ and SEQ papaya growing regions.

	NQ		CQ		SEQ	
NUTRIENT	**MEAN**	**CV%**	**MEAN**	**CV%**	**MEAN**	**CV%**
Total N(%)	1.05	53	1.46	32.5	1.6	60
NO_3-N mg/kg	1114	155	1748	121	1745	78
S %	0.25	35.1	0.50	18.7	0.38	91.1
P %	0.24	47.1	0.41	25.4	0.24	69.3
K %	3.22	30.8	5.51	23.5	2.95	83.4
Ca%	1.09	36.1	1.33	45.4	1.87	75.2
Mg %	0.50	46.4	0.50	26	0.65	68.1
Na%	0.09	57.3	0.67	86	0.26	165
Cl mg/kg	1.65	40.8	3.36	39.7	3.63	51.5
Cumg/kg	6	122	4	75	3	50
Zn mg/kg	15	62.2	23	38	22	39.2
Mnmg/kg	61	73.5	25	24	55	35.7
Fe mg/kg	41	82.8	18	56	33	49.8
Bmg/kg	24	29	25	19	38	58.1
Al mg/kg	14	145	4	98	21	105
Sample size	93		43		4	

N concentrations (Table 1) in petioles sampled in NQ are apparently lower than for both CQ and SEQ, and K concentrations also appear lower in NQ and SEQ. Both Tables are by no means complete data sets and are used only to illustrate very broad trends and the variability of mean values. The smaller number of samples for CQ and SEQ does not allow a true assessment of overall variability.

Table 2 Means and co-efficients of variation (CV%) for soil nutrient levels from NQ, CQ and SEQ papaya growing regions.

	NQ		CQ		SEQ	
NUTRIENT	**MEAN**	**CV%**	**MEAN**	**CV%**	**MEAN**	**CV%**
pH (1.5 water)	5.55	11.65	6.03	16.3	5.74	10.3
C%	2.58	156.5	2.2	19.3	2.53	12.7
N-NO_3 mg/kg	11.7	100.4	17.8	55.8	19.1	72.7
S mg/kg	126	123.2	33	64	15	69
P mg/kg	55	52.7	87	49	34	39
K meq .%	0.29	84.7	0.55	20	0.46	27.7
Ca meq.%	1.89	77.9	6.59	67	7.86	70.4
Mg meq.%	0.72	94.3	2.07	65	5.55	152
Al meq.%	0.34	127.4	0.01			
Nameq.%	0.04	57.5	0.76	85	0.30	90.9
Cl mg/kg	21	116.8	225	108	34	43
Elect. Cond. ds/m	0.26	165	0.59	107	0.08	34.3
Cumg/kg	2	125	4	64	0.84	53
Zn mg/kg	2.9	165	2.4	38.9	4.32	74.9
Mnmg/kg	22	162	13	79	12	93
Fe mg/kg	53	63	210	122	100	65
B mg/kg	0.3	177	0.16	57.4	0.39	65.6
Exch. Na%	1.3	-	7.4	-	1.8	-
CEC meq.%	3.09	55.8	10.29	49.1	16.2	93.2
BSP	84		91		87.5	
Sample size	49		7		18	

8.4 PROJECT OBJECTIVES

1. Determine the nitrogen and potassium requirements of papaya in north Queensland and extrapolate to other regions.

Specific objectives

- evaluate current petiole sampling methods
- determine young (pre-bearing) papaya nitrogen requirements
- determine mature papaya nitrogen and potassium requirements
- assess the nutrient balance of N and K under different levels of applications and define N and K efficiency ratios
- assess the impact of N and K applications on fruit quality
- define adequate soil and leaf nutrient levels and concentrations

2. Determine plant uptake and nutrient removal of macro-nutrients in papaya

Specific objectives

- establish temporal variations of total biomass and distribution of components
- establish temporal variations of nutrient contents and the distribution in components
- relate plant size to total nutrient requirements

- assess nutrient applications and management in relation to plant uptake and removal

3. **Assess the utility of quick test petiole sap analysis methods**

Specific objectives
- use a quick test methodology to evaluate its accuracy and potential to monitor N and K petiole status and nitrate N in soil
- establish improved nutrient management of N and K by fast, regular monitoring

4. **Define sustainable nutrient management practices for papaya production in Queensland.**

Specific objectives
- Combine and synthesise results from all studies to formulate sustainable nutrient management practices for North Queensland, and extrapolate these results to other regions.

CHAPTER 9: SAMPLING METHODOLOGY TO DETERMINE PAPAYA NUTRIENT STATUS

9.1 INTRODUCTION

For foliar analysis data to be useful, the sampling methodology must be standardised with respect to age and position of samples (index tissue), the number of units taken per sample, the area of plants used per sample, the washing and drying methodology and the analytical methods used. Awada (1969) established in Hawaii for papaya, petioles subtending the most recently opened flower as the index tissue for N, P and K analysis. In Cameroon, Marchal

(1986) established that the leaves from position 17 to 20 which subtended the most recently opened flowers were in zones of minimal nutrient changes. They did not however comment on sample size, but stated that it was necessary to sample the whole petiole rather than sections of it, due to variations in nutrient concentrations along the petioles. Petioles were used in the study herein reported, as the index tissue, and subsequent studies in this report.

In Queensland it is common practice for those involved in soil and leaf testing services, to collect 10 petioles per block (approx.0.5 to 1 ha). The validity of this practice needed evaluation for commercial foliar sampling, and it was necessary also to evaluate sampling requirements for 'quick test' methods of nutrient assessment. Two commercial farms in north Queensland (NQ) were chosen for this study.

9.2 METHODS AND MATERIALS

Petioles from hybrid 1E growing at the South Johnstone Research Station were collected in June 1995 to assess variations in N, P and K concentrations along petioles. Three samples of 3 petioles each were collected and sectioned into top, middle and bottom sections or thirds, dried, ground and analysed. The top end is the section where the petiole joins the leaf blade.

In April 1996, two commercial papaya farms near Innisfail (NQ) were sampled to determine the effect of petiole sample size and number of replicate samples on mean nutrient concentrations, and to assess the requirements for quick test methods. At farm number one, 700 plants (0.4ha) of 9 months age, were used as the sampling area. A total of 200 petioles were collected (from the petiole subtending the most recently opened flower) and random samples of different numbers drawn, with samples containing 10 petioles each. At farm number two, 200 petioles were also collected from 750 trees (0.4ha) of 8 months age, and samples grouped into 5 x 5 petioles sample sizes and 5 x 10 petioles sample sizes. Only one petiole was selected from each tree sampled. The equivalent sampling intensity from random samples of sample size (5 or 10 petioles) and number of samples (1, 2,3,4 or 5) taken together and bulked is indicated in Table 3.

All samples were washed in detergent, rinsed and then oven dried for 48 hours at 70°C, then ground to pass through a 2 mm mesh of a hammer mill. Dried samples were analysed at the NR&M laboratories in Mareeba, north Queensland.

Plant samples were digested using a Kjeldahl procedure. N and P were determined with a segmented flow analyser. K, Ca and Mg were determined with an atomic absorption spectrometer.

Table 3. Sampling intensity, petioles per hectare and trees per hectare, for samples taken per mean value, farm two sampled.

Sample size (petioles/sample)	Number of samples/mean	Sample intensity petioles/ha	% of trees sampled, per sample size
5	1	12	0.7
5	2	24	1.4
5	3	36	2.1
5	4	48	2.8
5	5	60	3.5
10	1	24	1.4
10	2	48	2.8
10	3	72	4.2
10	4	96	5.6
10	5	120	7.0

9.3 Results

The results of petiole sectioning sampling (Table 4) confirmed the results of Martin-Prevel et al.(1974) in establishing differences in concentrations along the petiole length.

Table 4. Variations in petiole N, P and K concentrations along petiole lengths.

Sample	N (%)	P (%)	K (%)
Bottom – mean	0.52	0.23	3.31
-stdev	0.028	0.02	0.12
-cv%	5.5	8.8	8.2
Middle – mean	0.54	0.23	3.01
-stdev	0.06	0.005	0.38
-cv%	11	2.5	12.6
Top-mean	0.88	0.33	4.51
-stdev	0.11	0.05	0.52
-cv%	12.4	15.4	11.5

Nitrogen, P and K were all much higher in top portions, with the other two sections similar. Some growers sample the middle 1/3 section and this might be associated with lower than expected concentrations.

Sampling intensity (size and replication) was found to have little effect beyond 3 replicates on nutrient concentrations for N and P, resulting from 5 and 10 petiole sample sizes. For K, consistent significant differences were found. In all cases, the use of smaller sample sizes (5 petioles) resulted in lower petiole concentrations. From Table 5, petiole N (%) was found to be consistent (cv <7%) across 10 petioles/sample size (22 petioles /ha) for both farms, and 5 petiole samples (11 petioles/ha) gave similar results to the 10 petiole size samples at farm 2 (Table 3). At 1 and 2 samples per mean, the 5 petiole samples (Farm 2) gave lower concentrations than the 10 petiole samples, but significance not confirmed.

The current commercial sampling intensity is about 10 petioles per block equivalent to a single 5 petiole sample, and this practice may be associated with lower N concentrations (Fig 5(a)). Nitrogen concentrations were considerably lower at farm 1, and all are equivalent to the intensity of a single10 petiole sample from farm 2.

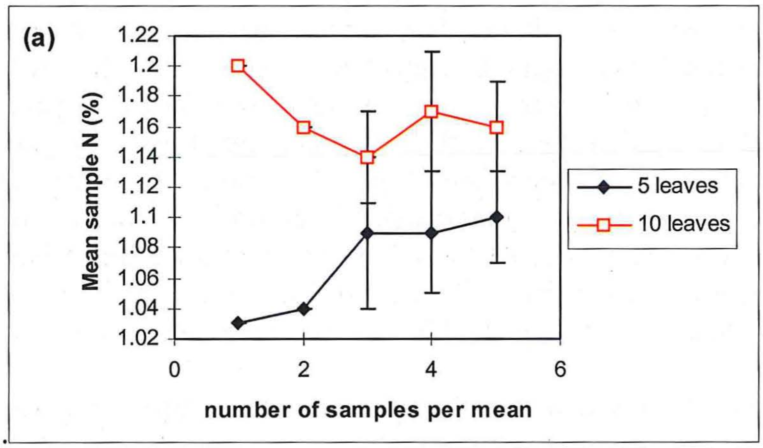
Concentrations of P for the mean of 5 and 10 petiole samples were similar at farm 2, and showed little effect of sampling intensity on concentrations (Fig 5(b)). The cv across 10 samples was 6.94% at farm 1, attesting to the small impact of samples sizes as measured, but higher for farm 2, as were P concentrations. Potassium (Fig. 5(c)) indicated some significant differences similar to the nitrogen trend, with 10 petiole size samples always of higher concentration than 5 petiole samples, at farm 2. For farm 1, K(%) concentrations were much lower than farm 2, and cv was also low across samples for both farms. Current sampling practices may be associated with lower K concentrations (Fig 5(c)), and again the farm 1 samples were of significantly lower K concentrations. Calcium and magnesium showed similar trends with 5 petiole samples consistently of lower concentrations than 10 petiole samples (Fig 5(d),(e)). Both farms indicated low cv's (<8%) for both nutrients. Nitrate was very low at farm 1, thus not of much value in comparisons. At farm 2, nitrate was different in both sample sizes, but the trend was not consistent (Fig. 5(e)). The cv's were high (16-33%) regardless of sample set, and indicate the highly variable nature of this property.

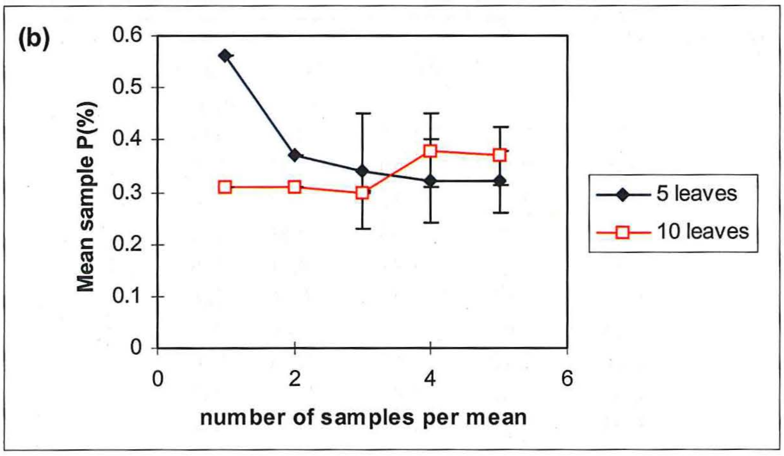
Table 5. Petiole analysis data from Farms 1 and 2 used to assess sample variation

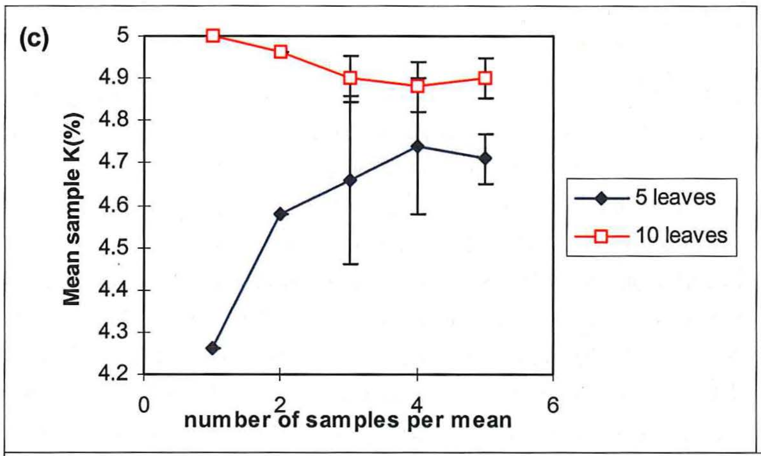
			Laboratory data				
Petioles / Samples	Farm sample	N %	P %	K %	Mg %	Ca %	Nitrate mg/kg
10	farm1-1	0.74	0.20	2.66	1.48	0.57	228
10	farm1-2	0.69	0.19	2.55	1.30	0.55	228
10	farm1-3	0.67	0.20	2.58	1.40	0.47	228
10	farm1-4	0.67	0.20	2.79	1.34	0.51	228
10	farm1-5	0.73	0.19	2.71	1.42	0.51	228
10	farm1-6	0.78	0.20	2.46	1.33	0.56	228
10	farm1-7	0.75	0.21	2.61	1.35	0.46	228
10	farm1-8	0.69	0.16	2.42	1.37	0.47	346
10	farm1-9	0.70	0.20	2.61	1.42	0.56	232
10	farm1-10	0.76	0.21	2.72	1.53	0.55	564
10	farm1-11	0.78	0.20	2.66	1.63	0.51	228
10	farm1-12	0.74	0.22	2.77	1.34	0.54	228
10	farm1-13	0.70	0.20	2.67	1.34	0.52	228
10	farm1-14	0.73	0.19	2.43	1.52	0.53	280
10	farm1-15	0.76	0.22	2.53	1.27	0.50	228

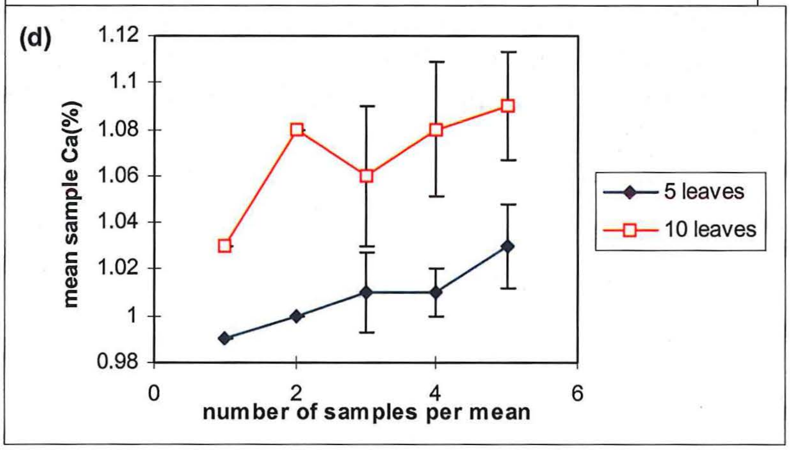
10	farm1-16	0.71	0.20	2.61	1.59	0.54	228
	mean	0.72	0.20	2.61	1.41	0.52	259.88
	sd	0.037	0.014	0.112	0.108	0.034	86.904
	cv%	5.04	6.95	4.29	7.62	6.62	33.44
5	farm2-1	1.03	0.56	4.26	0.99	0.62	3252
5	farm2-2	1.05	0.18	4.89	1.02	0.73	3123
5	farm2-3	1.20	0.26	4.83	1.04	0.71	3184
5	farm2-4	1.10	0.29	4.96	1.01	0.71	2433
5	farm2-5	1.14	0.31	4.63	1.09	0.76	1830
	mean	1.10	0.32	4.71	1.03	0.70	2764.40
	sd	0.069	0.143	0.280	0.039	0.054	617.52
	cv%	6.26	44.58	5.95	3.81	7.63	22.34
10	farm2-6	1.20	0.31	5.02	1.04	0.73	2940
10	farm2-7	1.12	0.31	4.90	1.13	0.76	2025
10	farm2-8	1.09	0.30	4.83	1.04	0.69	2408
10	farm2-9	1.27	0.60	4.77	1.15	0.71	3111
10	farm2-10	1.14	0.35	4.98	1.09	0.73	2756
	mean	1.16	0.37	4.90	1.09	0.72	2648.00
	sd	0.072	0.127	0.104	0.051	0.025	435.036
	cv%	6.17	34.12	2.13	4.65	3.48	16.43

Figure 5. Mean sample (Farm 2) concentration of leaf petioles, in relation to sample size (number of leaves) and samples per mean for (a) N%, (b) P%, (c) K % (d) Ca% (e) Mg% and (f) nitrate. SE bars are indicated.

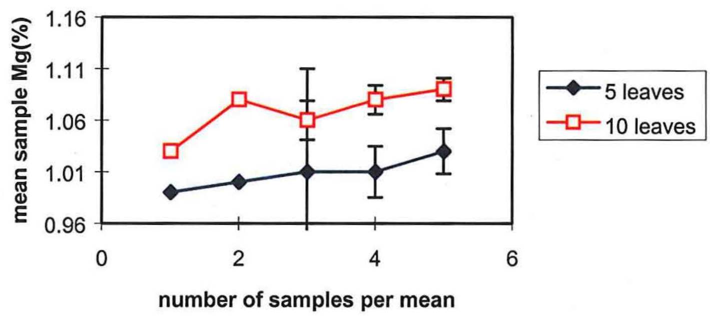


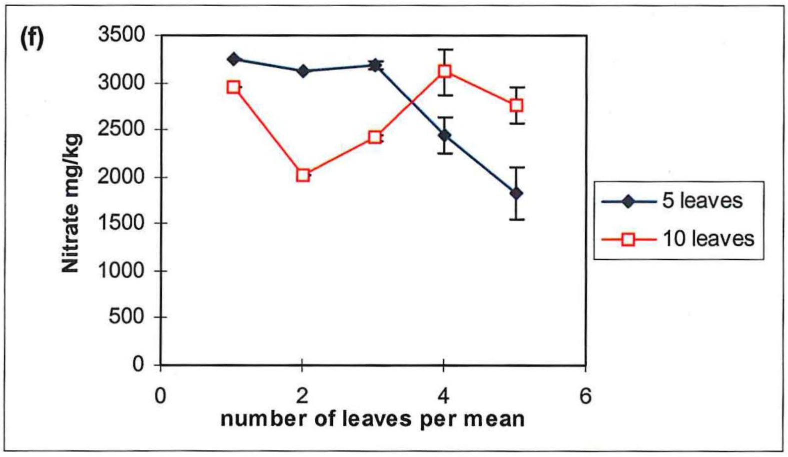



(c)
Mean sample K(%)
number of samples per mean
5 leaves
10 leaves


(d)
mean sample Ca(%)
number of samples per mean
5 leaves
10 leaves

(e)


mean sample Mg(%)
number of samples per mean
5 leaves
10 leaves


(f)
Nitrate mg/kg
number of leaves per mean
5 leaves
10 leaves

9.4 Discussion and conclusions

Literature studies on papaya nutrient analysis unfortunately do not reveal suggested sample sizes and intensity, nor are there apparently any data relating nutrient concentrations to sample size. In fertiliser trials Awada and Long (1969) used 2 petioles per sample plot in a trial of 162 trees, with only 3 trees per plot, thus revealing very intense sampling intensity. Results from this work suggest that N, P and K may suffer from reduced concentrations at sampling intensities as currently employed commercially. For this reason it is recommended, that at least 20 petioles per hectare (i.e. 2 samples of 10 petioles each, or 4 samples of 5 petioles each etc. from different parts of the block), or equivalent intensity of sampling be used for papaya foliar analysis. This would cover the requirements of all the macro-nutrients. At 20 petioles per hectare, about 1.2% of trees would be sampled, and this seems to be more representative than using 0.6% of trees with 10 petioles per hectare. It is recommended to use the whole petiole for sampling, rather than sub-sampling for analysis.

CHAPTER 10: PAPAYA NITROGEN AND POTASSIUM USE EFFICIENCY, AND YIELD RESPONSES TO APPLIED FERTILISERS.

10.1 INTRODUCTION

A survey of grower nutrient management practices was completed in 1995 (Richards *et al.* 1995) for major papaya growing areas in north, central and southeast Queensland. The rates of applied fertilisers were found to be highly variable across farms, regardless of soil types, and many growers appeared to be applying unnecessarily high rates. The industry agreed on the need to rationalise fertiliser usage.

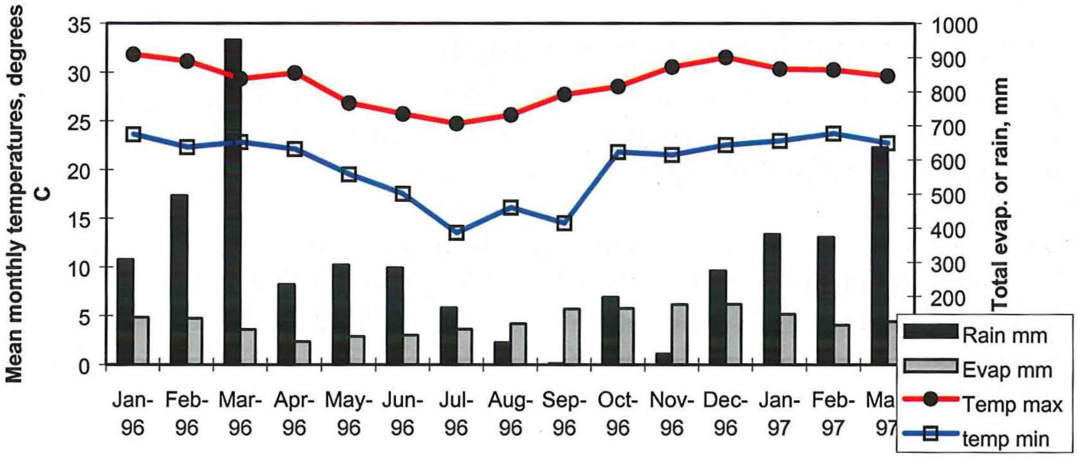
No fertiliser response trials have been established in Australia for papaya and current recommendations are based upon limited survey work from southeast Queensland (Robinson 1986). These will often be inappropriate for NQ growers in particular, due to vastly different soil types and climates. Papaya plants are fast growing, producing fruit from the 7 month onwards for harvest for up to 2 years or more. Nutrient demand is expected to be high and under fertilising may result in yield and quality losses, whereas over fertilising will be wasteful, give rise to excessive vegetative growth and may impact on fruit quality.
In this context the papaya industry commissioned trials to validate existing practices and to define nutrient requirements for papaya in Queensland.

10.2 MATERIALS AND METHODS

10.2.1 LOCATION, CLIMATE AND SOIL PROPERTIES

A nutrition trial with papaya (*Carica papaya)* plants, was conducted at the Queensland DPI's South Johnstone Research Station, north Queensland, Australia (17 ° 36' 30" S, 146 ° 00' 30" E) from January 1996 to March 1997. Details of monthly weather data from January 1996 through to March 1997 are shown in Fig. 6.

Figure 6. Mean monthly maximum and minimum temperatures, and total monthly rainfall and evaporation at SJRS.



The soil type is classified as a Red Ferrosol (Uf 6.31, krasnozem, red volcanic) belonging to the Mundoo series (red structured, uniform textured, clay loam derived from basalt). Each of 60 plots were sampled (0-15cm) for pH, exchangeable cations, electrolytic conductivity and available P, with mean block values (20 samples each) as Table 6.

Table 6. Pre-trial levels of soil nutrients, sampled September 1995.

	avail P mg/kg	**Exch. K cmol(+)/ kg**	**Exch. Ca cmol(+)/ kg**	**Exch. Mg cmol(+)/ kg**	**pH 1:5 soil: water**	**Electrolytic conductivit y (dS/m)**
Block 1						
mean	147	0.40	1.83	0.55	4.8	0.11
cv%	44.8	25.5	25.9	14.9	3.0	22.5
Block 2						
mean	136	0.38	1.79	0.50	4.7	0.12
cv%	20.4	19.7	33.9	21.8	2.2	19.9
Block 3						
mean	140	0.36	1.78	0.49	4.8	0.11
cv%	16.9	24.0	32.9	23.5	2.0	19.3

10.2.2 Plantation Management

The trial was established using 1B hybrid papaya plants, transplanted to the field in October 1995. Planting density was 1666 plants per hectare, in single lines at 4 m intervals and with 1.5 m plant spacings. From October 1995 to Jan 1996 all plants received a total of 50 g each of N, P & K per plant. Lines were mounded at 0.4m height and 2m width at the base. About 10% of plants were male pollinating plants. Limestone application (5t/ha, ~ 1850 kg Ca/ha) was broadcast in March 1996, and 200g/plant MgO (approx. 180 kg Mg/ha) applied in November 1996, by hand. Micro-nutrient foliar sprays of Zn, Fe and B were applied at 3 monthly intervals. Trees were sprayed as required to control insects, herbicide application was monthly and trees with viral disease symptoms cut out and removed. Each tree was irrigated with a 40 litre/hour micro-sprinkler and irrigation scheduled based upon weekly neutron probe measurements and the plant available water capacity in the top 40 cm of soil.

10.2.3 Experimental Design and Treatments.

The trial was established as a factorial experiment, with 5 rates of nitrogen, 4 levels of potassium and 3 replicates, arranged in a randomised complete block design. There were 12 trees per plot, with 2 guard trees between each plot.

There were a total of 20 treatment combinations and 60 plots total. Fertiliser treatments commenced in January 1996, through to the last application (monthly basis) in February 1997, with rates of application listed as Table 7. Nitrogen was applied as ammonium nitrate and K as potassium chloride initially and later as sulphate.

10.2.4 HARVESTING AND FRUIT QUALITY ASSESSMENT

Harvesting commenced May 1996 and was completed 25/03/97, some 2 months earlier than planned due to cyclonic activity (Cyclone Justin) late in March 1997. Treatment plots were harvested twice weekly to collect fruit yield, number and mean fruit size data. Yield data was reduced to mean yield in kg per tree. Although each plot commenced with 12 trees each, losses due to viral diseases were typically 35%, reducing mean plot size to 5-10 trees.

Table 7. Total fertiliser nitrogen and potassium application details

Nutrient rate/level	N or K g/tree Jan 96-Jun 96 (Treatment commencement -> harvest commencement)	N or K g/tree Jul 96- Mar 97(Harvest commencement --> trial completion)	Total N or K kg/ha applied
N1	50	20	116
N2	112	65	292
N3	195	163	591
N4	295	228	863
N5	419	292	1,173
K1	38	32	116
K2	99	78	292
K3	178	170	574
K4	280	245	866

In September and December 1996, and in March 1997, fruits were harvested from selected treatment trees and assessed for size, TSS (^{o} Brix), firmness and eating quality. A minimum of 2 and a maximum of 8 fruits per plot were collected per recording period, and both plots of selected treatments averaged. Firmness was measured using fruit halves and a fruit penetrometer, with 4 measurements per fruit half. Total soluble solids was determined using a hand held refractometer using juice from the petal scar fruit end. Eating quality was assessed by two people using the criteria of 1=very good, 2=good, 3=fair, 4=acceptable and 5=unacceptable.

10.2.5 GROWTH AND BIOMASS PARTITIONING

Growth of trees was recorded as stem girth marked 15 cm above the ground, and as height to the crown, with 4 trees each from all 3 replicates of treatments N1K3, N2K3, N3K3, N4K3 and N5K3 recorded fortnightly from 8/02/96 to 27/06/96 thereafter monthly. Trunk cross-sectional area (TCA) was derived from the stem girth (diameter) measurement. In April 1997 all plants were measured to determine crop load per treatment. On 17 April 1997, three trees each from treatments N1K3, N2K3, N3K3, N4K3 and N5K3 were destructively sampled into components of leaves, petioles, stem and fruits. For all trees individual fresh weights of each component were measured in the field and mixed samples of each component taken for dry matter determination at 70-80 ^{o}C over 4 days. Bulked samples for each rate of N were taken from the three trees for nutrient content determinations. Adjustments for root biomass and nutrient content were made using the results of previous work (Richards 1998) which showed that 15 month old papaya plants had a mean root/tops ratio (dry weight) of 0.18 and mean root nutrient concentrations of N=1.10%, P=0.19%, K=3.1%, Mg= 1.17% and Ca =0.77% . Adjustments for fruit biomass removal and associated nutrient loss were also calculated based upon mean green mature fruit concentrations and fruit harvested for each treatment during the trial.

10.2.6 PLANT AND SOIL ANALYSIS.

Commencing in February 1996, monthly petiole samples from treatments N1K2, N2K2, N3K2, N4K2 and N5K4 were collected using three petioles from each plot and sampling each plot separately. Petioles subtending the most recently opened flower were utilised as established by Awada and Long (1971b) and petioles were sampled in preference to leaves as recommended by Awada and Long (1971b). All samples were washed in detergent, rinsed and oven dried at 65-70° C for 3 days, ground in a hammer mill then analysed. Plant samples were digested using a Kjeldahl procedure. N and P were determined with a segmented flow analyser. K, Ca and Mg were determined with an atomic absorption spectrometer.

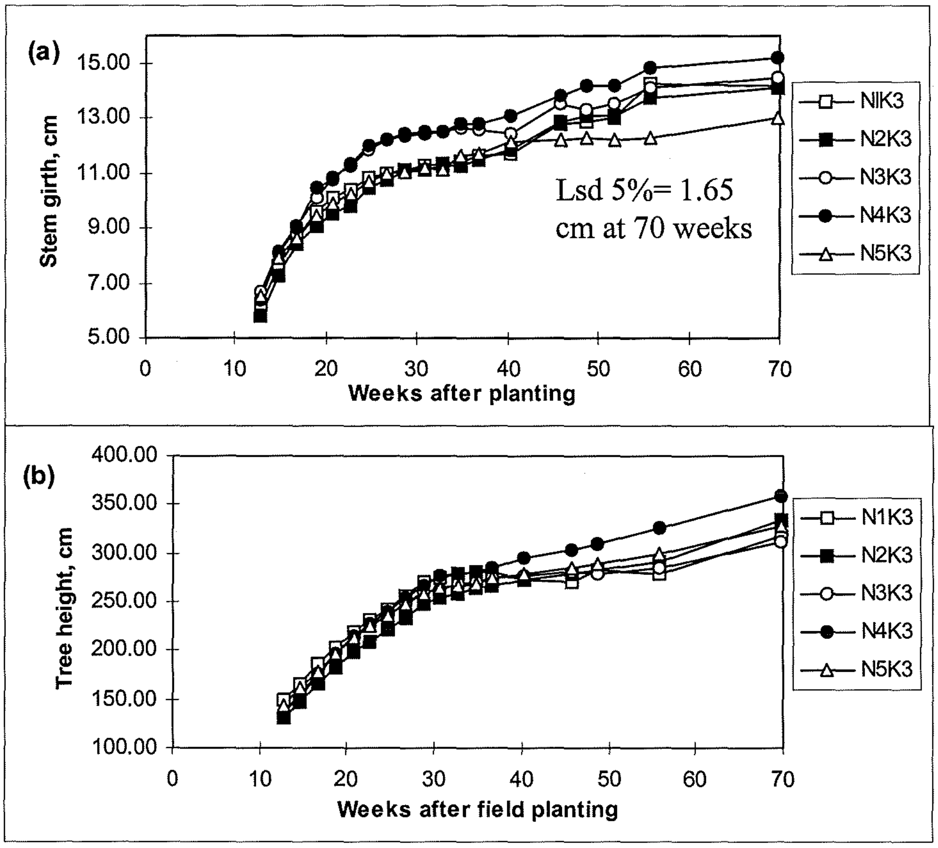
Additional petiole samples from all plots were collected in May and September 1996, and in March 1997. Samples from destructive harvesting were treated as above. Soil samples (0-15 cm) were collected in October 1996 and March 1997, by collecting 4 cores per plot and bulking over three plots for 20 treatment samples. Additional samples for nitrate-N and pH were regularly collected from treatments N1K2, N2K2, N3K2, N4K2 and N5K2. Soils were oven dried at 40 $^{\circ}$ C for 2 days before grinding and sieving to the <2mm fraction, for analysis. Nitrate N was determined on field moist soil the day after sampling, following overnight refrigeration. The method 7C2 of Rayment and Higginson (1992) was used.

10.3 RESULTS

10.3.1 GROWTH RESPONSES

Figures 7 (a) and (b) show growth data from week 12 to week 70 for treatments N1 to N5 at the K3 level. Differences in both girth and height were small across treatments with all showing similar sigmoid type growth responses. In a N fertiliser response trial in Hawaii, Awada (1969) did not find any differences in stem circumference across a wide range of applied N.

Figure 7. Time courses of (a) stem girth and (b) stem height for means of treatments



10.3.2 YIELD RESPONSES

Figure 8 captures the essence of the trial results showing that large applications of nitrogen were wasted and did not increase yield. Yields are relative to N3K3 plots. Best results were obtained using N2 rates (292 kg/ha/21 months, ≈170 kg/ha/yr) and above and possibly with K3 levels. The treatment N3K3 gave significantly higher yields than many other treatments and K3 means were significantly higher than K2 and K1 (Table 3). Table 3 also clearly shows that treatments N2, N3, N4 and N5 gave similar mean yields and all were significantly higher than N1 treatment means. All yields were higher than or similar to, the industry average of 52kg/tree as established by survey (Richards *et al.* 1995), reported overseas of 54t/ha (Reddy and Kohli 1989) and 91kg/tree maximum yield (Awada and Long 1971b).

The response to K3 across N rates is different than that of other K rates, rising slowly to a peak at N3K3 and falling thereafter. In contrast, at other levels of K the peak is reached at N2 rates of application.

Figure 8. Changes in relative yield with kg/ha of N applied.

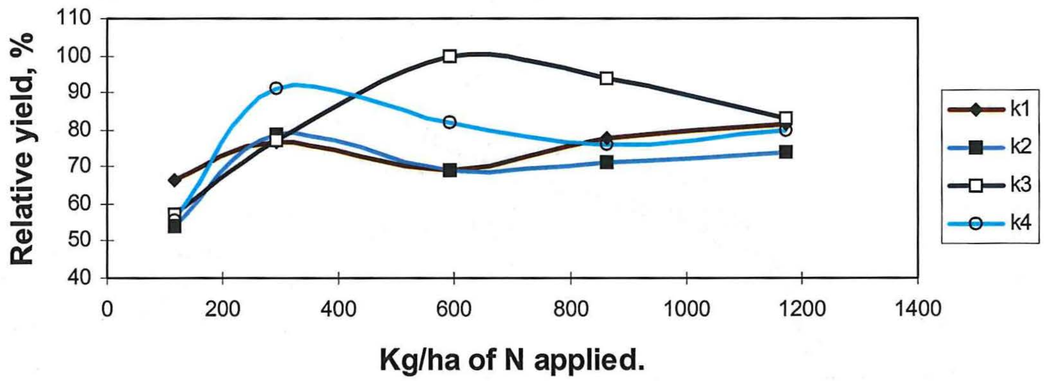


Table 8. Treatment mean yields, fruit sizes from papaya nutrition trial.

Treatment	Mean yield kg/tree	Mean yield tonnes/ha	N rates means kg/tree	K level means kg/ha	Fruit size kg	N rates mean fruit size	K level mean fruit size
N1K1	62.52	93.7			1.16		
N1K2	50.87	76.3			1.07		
N1K3	54.00	81			1.17		
N1K4	52.45	78.6	54.96		1.14	1.137	
N2K1	71.98	107.9			1.08		
N2K2	73.99	110.9			1.12		
N2K3	72.73	109			1.23		
N2K4	85.87	128.5	76.14		1.18	1.151	
N3K1	64.81	97.2			1.10		
N3K2	65.01	97.5			1.14		
N3K3	93.93	140.8			1.19		
N3K4	77.14	115.6	75.23		1.11	1.135	
N4K1	73.01	109.5			1.16		
N4K2	66.85	100.3			1.10		
N4K3	87.86	131.8			1.16		
N4K4	71.47	107.1	74.82		1.10	1.130	
N5K1	76.33	114.4			1.07		
N5K2	69.20	103.8			1.09		
N5K3	78.19	117.3			1.15		
N5K4	75.22	112.8	74.73		1.11	1.106	
K1				69.73			1.114
K2				65.20			1.103
K3				77.34			1.180
K4				72.43			1.131
Lsd 5%	17.95		8.97	8.00	0.092	0.046	0.041

10.3.3 Fruit quality responses

An indication of the lack of response of papaya fruit quality parameters to applied N and K fertilisers, is shown in Tables 8 and 9.

Table 9. Fruit quality parameters averaged over sampling times and replicates for representative treatments

Treatment	TSS Brix °	Fruit firmness lbs pressure	Eating quality
N1K2	9.2	2.7	2.9
N2K2	8.3	2.5	3.0
N4K2	9.3	2.9	2.7
N5K2	9.2	2.5	3.1
N3K1	8.1	2.1	2.7
N3K2	8.9	2.4	3.2
N3K3	8.5	2.6	3.0
N3K4	8.2	2.6	3.1
LSD 5%	1.3	0.59	NA

Fruit size averaged across N rates was not significantly different between rates, however fruit size averaged across K3 levels was significantly higher than for all other rates, although differences were not large nor of commercial concern.

Selected treatments studied (Table 9) did not show any differences in TSS, fruit firmness or eating quality. Such data were collected over three sampling periods and averaged, and these results suggest that papaya fruit quality did not change appreciably with seasonal or treatment effects.

10.3.4 Soil nutrient status and yield responses

Analysis of soil samples from March 1997 at the conclusion of the trial indicated large differences across both N and K treatments (Table 10, Fig 9). Soil pH(1:5) declined with increasing N rates but would have be en affected by variable soil ionic strength. Electrical conductivity rose rapidly with N rates, to reach high and possibly limiting values of >0.40 dS/m. Exchangeable Ca and Mg were always higher at the low rates of N, with K levels not having much impact except at the N1K1 treatment which recorded the highest values for Ca and Mg. Calcium levels reached low levels at N2 rates and above, despite lime applications. This fact combined with initially low pH levels makes pH management very important in this soil type, and in particular in relation to trials and confounding of treatment effects. From this trial it is apparent that managing Ca, Mg and pH and its impact on papaya growth and yield is not known, nor are the effects on the N xK trial results. Suffice to say keeping pH above 5.5 is desirable and this corresponds to pH attained with N2 and N1 rates. Magnesium levels were generally higher than were Ca possibly as a consequence of MgO applications used to raise pH. Magnesium levels generally were inversely related to available levels. Nitrate N as expected rose rapidly in accord with N rates to very high levels of 158 mg/kg. Exchangeable K increased with levels dramatically but the effect decreased as rate of N applied increased. K levels were significantly lower in the high N rate treatments. Soil exchangeable K and yield were not related as shown in Figure 11. Relative yields and soil nitrate N were related (Figure10). Since the start of the trial, generally, pH levels remained the same or increased, EC values increased, Avail

P remained the same, exchangeable K and Mg increased and Ca decreased. The lack of impact of liming and Mg materials to raise pH at the higher N rates was evident from this trial, despite that ammonium nitrate was the primary source of N.

Figure 9: Variation in nitrate N, and ammonium N and pH in soil from 5 N rates at 4 sampling times. (0-15 cm sample)

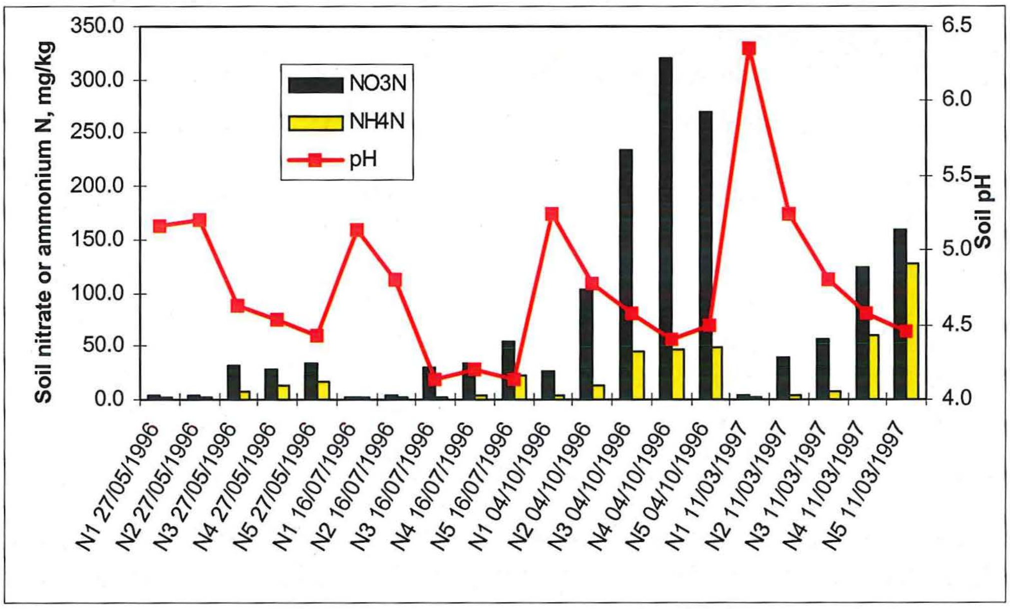
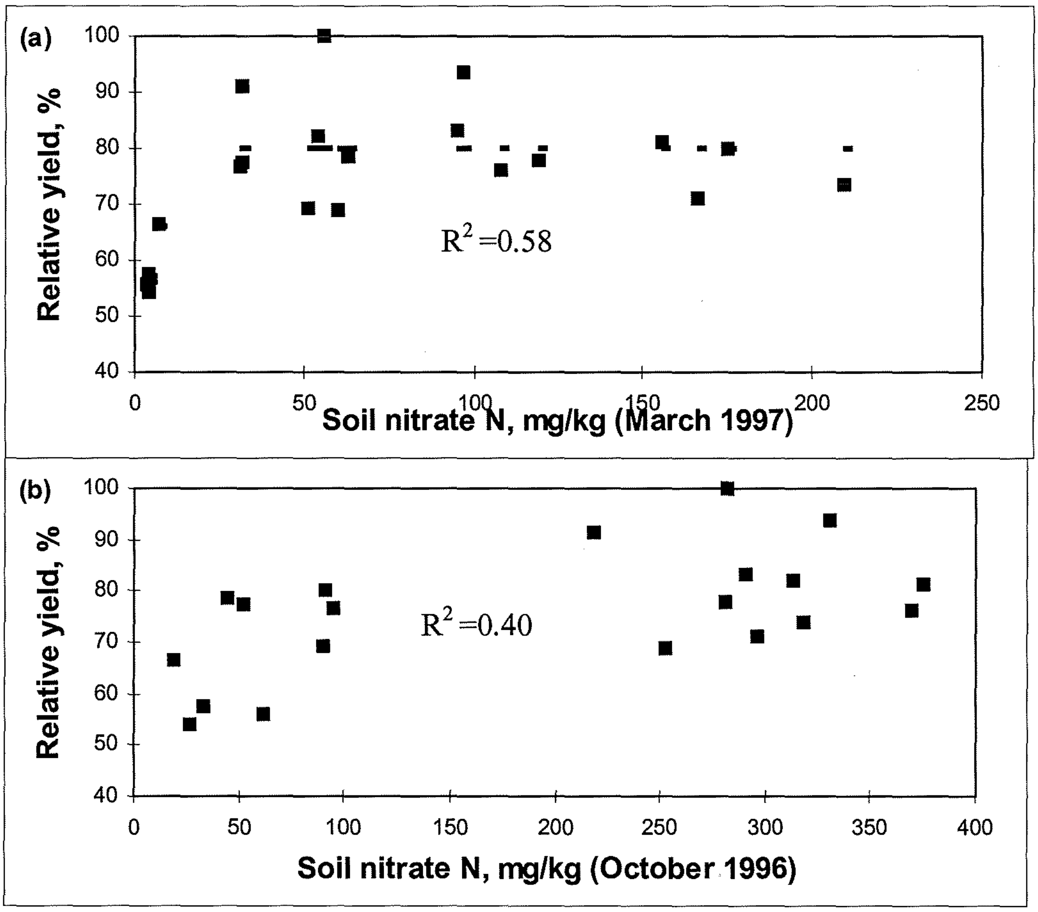


Table 10. Soil data from treatment means in March 1997, bulked from three replicates.

	Level of K				
	K1	**K2**	**K3**	**K4**	**Mean (N)**
EC dS/m					
N1	0.11	0.11	0.15	0.15	0.13
N2	0.13	0.19	0.23	0.23	0.195
N3	0.24	0.19	0.23	0.26	0.23
N4	0.32	0.39	0.33	0.38	0.35
N5	0.40	0.52	0.39	0.48	0.45
LSD 5%.......					0.06
Mean (K).....	0.24	0.28	0.26	0.30	
Exch Ca meq%....					
N1	1.11	0.76	0.75	1.18	0.95
N2	0.68	0.39	0.93	0.39	0.59
N3	0.32	0.16	0.20	0.30	0.24
N4	0.24	0.23	0.44	0.46	0.34
N5	0.54	0.75	0.79	0.61	0.67
LSD 5%......					0.27
Mean (K).....	0.58	0.46	0.62	0.58	
Exch. Mg meq %					
N1	6.52	5.60	3.02	4.43	4.89
N2	2.96	2.25	5.26	2.80	3.37
N3	1.56	3.24	2.84	1.78	2.35
N4	2.05	1.95	2.28	3.02	2.32

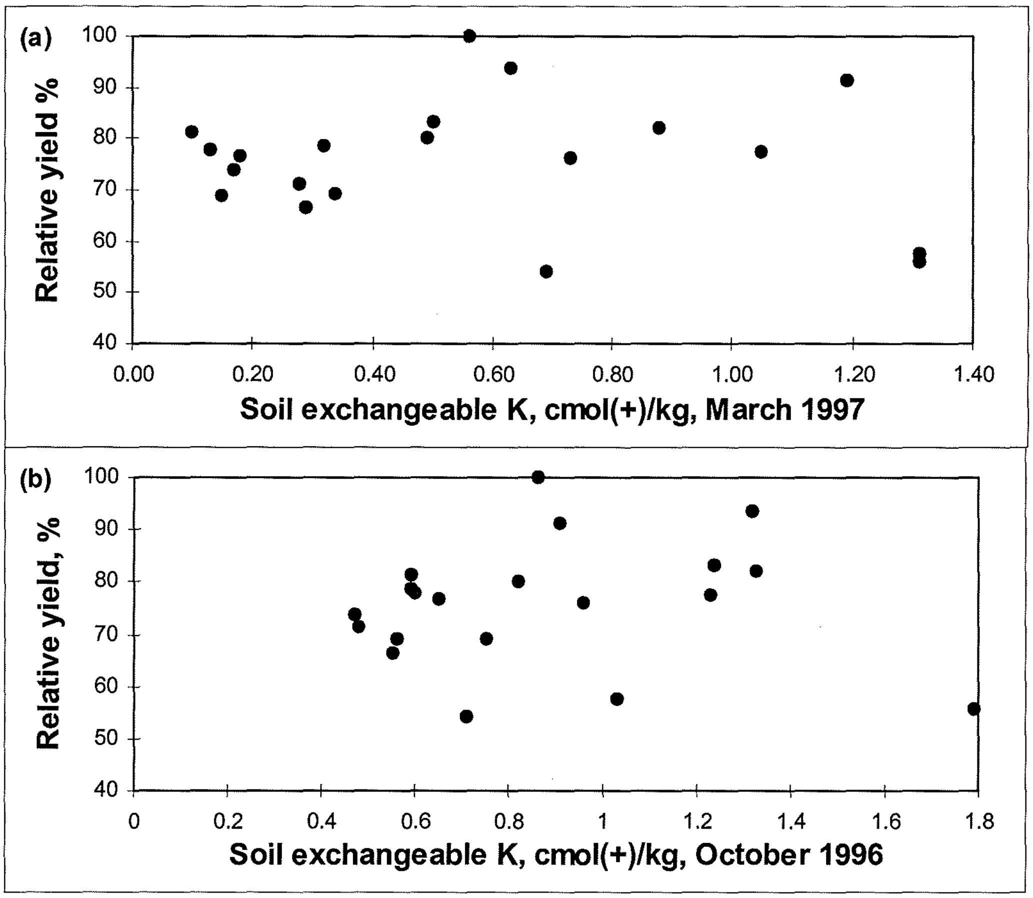
N5	2.07	1.23	1.55	1.11	1.49
LSD 5%.......					1.71
Mean (K).....	3.03	2.85	2.99	2.63	
Exch. K meq %.....					
N1	0.29	0.69	1.31	1.31	0.89
N2	0.18	0.32	1.05	1.19	0.68
N3	0.15	0.34	0.56	0.88	0.48
N4	0.13	0.28	0.63	0.73	0.42
N5	0.10	0.17	0.50	0.49	0.31
LSD 5%					0.23
Mean (K)	0.17	0.36	0.81	0.92	

Figure 10. Changes in relative yield with soil nitrate for (a) March 1997 and (b) October 1996.



Figures 10 (a) and (b) show the response of papaya relative yield to soil nitrate N levels in March and October 1997 respectively. The adequate level of nitrate N suggested from this data is 30 mg /kg or higher based on 10(a) where the regression was significant and stronger than for 10 (b)

Figure 11. Changes in relative yield with soil exchangeable K for (a) March 1997 and (b) October 1996.

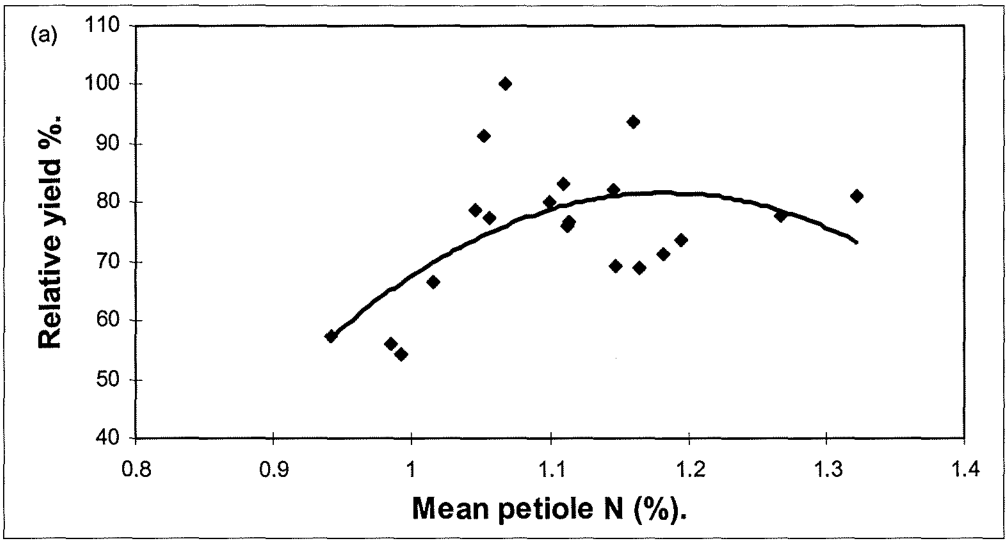


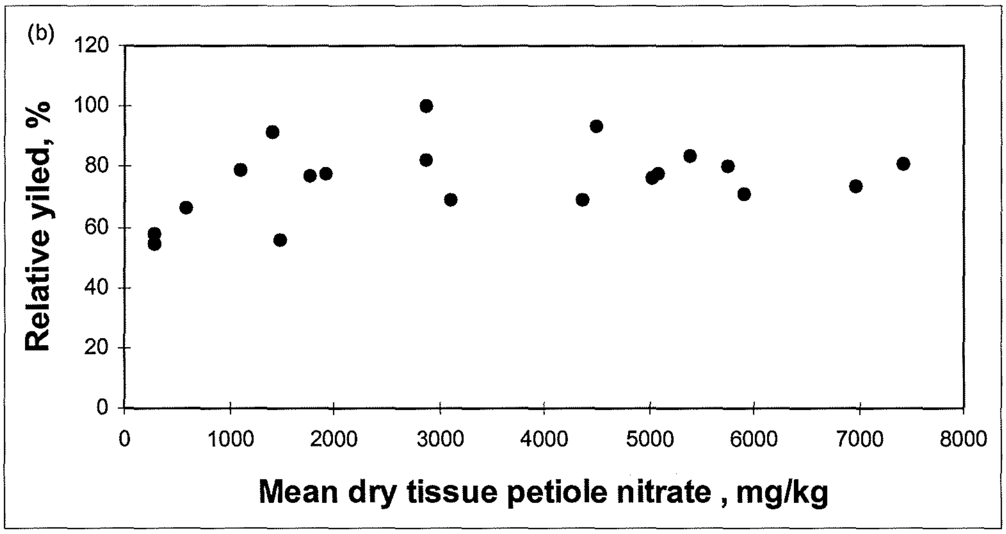
10.3.5 YIELD RELATIONSHIPS WITH PLANT NUTRIENT STATUS

Graphical presentation of relative yield with mean petiole N%, petiole nitrate and mean petiole K% (Figures 12(a),(b) and (c)) using means derived from February, May and October 1996 and March 1997 , did not show any significant linear or non-linear regressions. Individual month data also did not show significant regressions. Adequate levels were obtained using Cate-Nelson plots, giving petiole N of 1.05%, and petiole K of 3.5%. For the other macro-nutrients the Cate-Nelson method established adequate petiole P at 0.27%, Ca at 1.15% and Mg at 0.8% (data not shown).

Quick test methods were evaluated in this trial and good results obtained for the regressions of petiole sap nitrate N and K as measured by the RQFlex equipment and standard laboratory digest extractions (Figures 13(a)). Petiole samples collected in March 1997 from each plot were split longitudinally with half the sample sent to the laboratory and the other half used for RQFlex analysis. The data from RQFlex were averaged over treatments and plotted against mean yields per tree (Figures 13 (b)), with the sap nitrate N data explaining 54% of yield variation. There was no similar relationship obtainable with petiole sap K, despite removing N1 plots from the analysis, and the Cate -Nelson method gave an adequate concentration of 0.5g/l petiole sap. The adequate level of sap nitrate N is 35 mg/l, which when regressed to petiole nitrate (Figure 13(b)) equates to 1680 mg/kg.

Figure 12. Changes in relative yield with (a) mean petiole N%, (b) petiole nitrate N and (c) mean petiole K %.(Polynomial line of best fit for combined dates Feb, May, Oct and Mar 97)


(a)
Relative yield %.
Mean petiole N (%).


(b)
Relative yiled, %
Mean dry tissue petiole nitrate , mg/kg

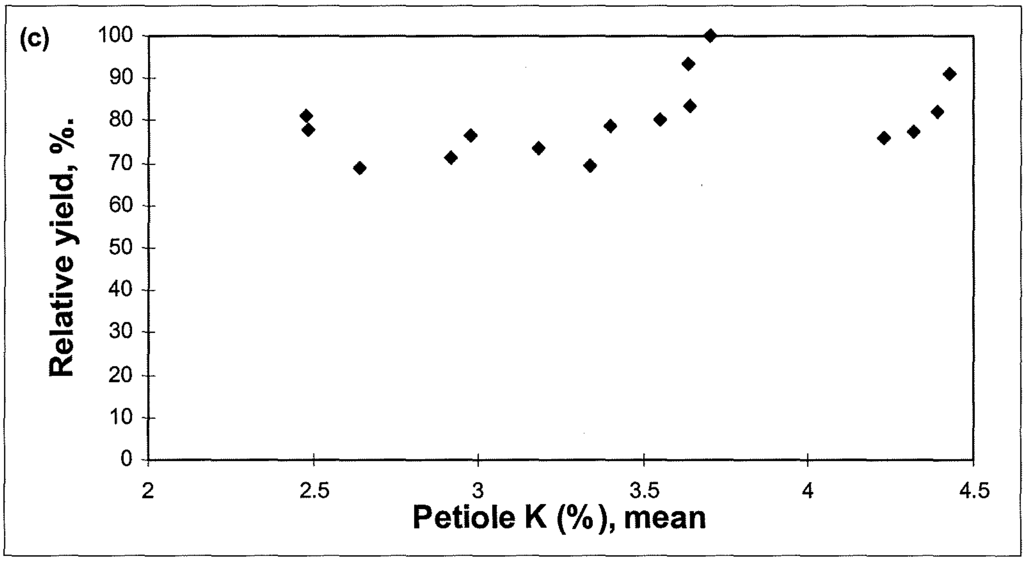
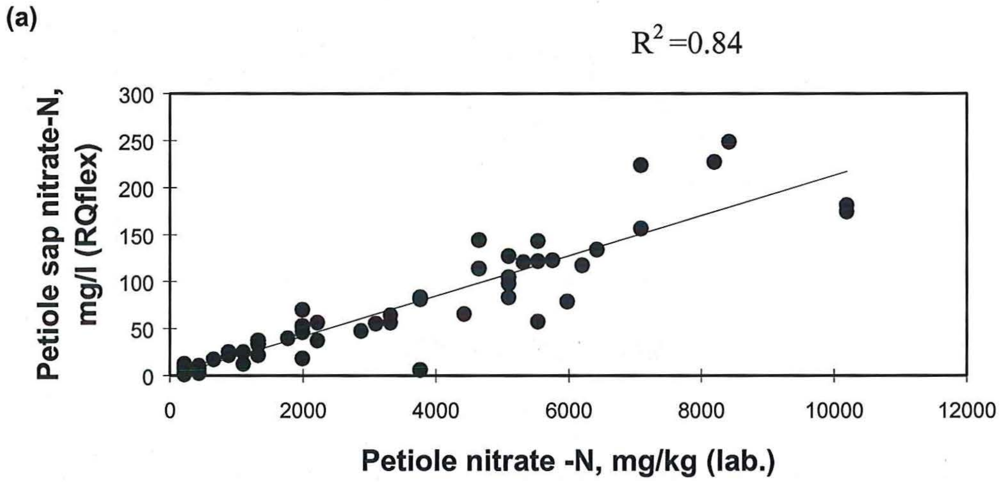
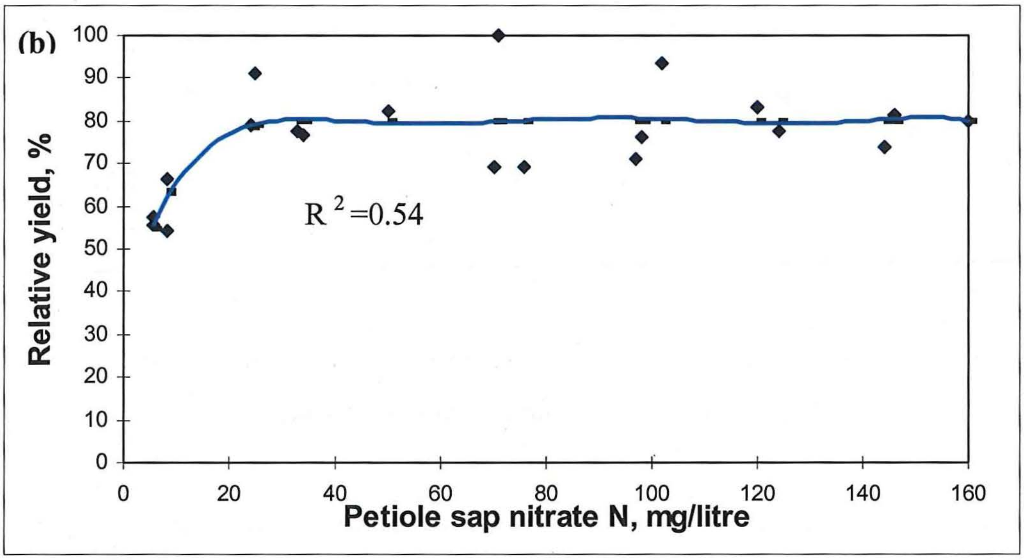

(c)
Relative yield, %.
Petiole K (%), mean

Figure 13. Changes in (a) petiole sap nitrate N (RQFlex) with petiole sap nitrate (laboratory) and (b) mean yield with petiole sap nitrate N (RQFlex).in March 97 when test was finally done for standard samples i.e. petiole subtending most recently opened flowers.





10.3.6 Temporal variations in plant nutrients

The results of monthly sampling of papaya petioles from three treatments (Figure 14 (a)..(e)) illustrate significant differences in N and K concentrations with N1 having lower N and higher K concentrations than N 5, and N3 intermediate. Calcium and magnesium concentrations were quite similar across treatments but showed large variations over time. Petiole P was mostly much higher in N1 treatments and this is probably related to improved P availability associated with higher soil pH, although Colwell soil tests indicated high available P in all samples (but pH of test solution> pH soil solution).

Nitrogen concentrations reached a peak in June 1996 in the second month of harvesting, declining gradually thereafter. This trend was also apparent for K and suggests that as cropping progresses, the uptake of N and K through crop removal tends to diminish plant nutrient supplies, despite N and K applications over the period. Nutrient dilution as a consequence of increased plant biomass is also a possibility.

At the start of flowering in February 1996 petiole N concentrations in N5 samples (Fig 14 a) were much higher than those of both N3 and N1, which were both low at <1.2%N. By the start of harvesting in May 1996, N5, N3 and N1 showed similar concentrations in the range 0.9 to 1.2%N. As fruiting progressed both N5 and N3 concentrations increased well above those of N1 with all concentrations reaching a peak in June 1996.

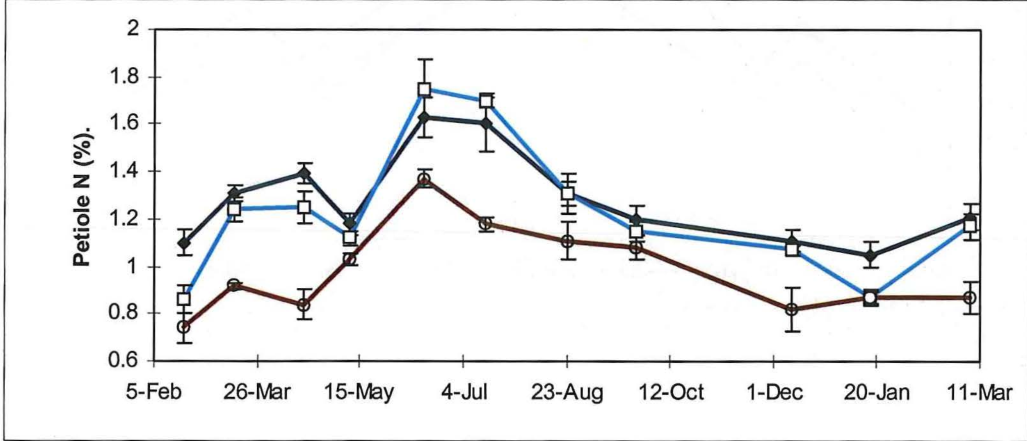
There were no significant regressions established between leaf N and K concentrations and yield at any time. For leaf K N1 rates gave higher K% than did either N3 and N5 rates at the K2 levels tested. All showed similar trends with the peak leaf K of 4.1% for N3 in April (early flowering). Since N2 rates and above gave similar mean yields and all higher than N1, following the trend of N3 sample data is of interest (ie data for N3K2) This suggests that sampling monthly from flowering (Feb 96) through to second month of harvesting (June 96) is warranted. Examination of data over this period allows defining of adequate concentrations and could serve as a check for commercial nutrient management programs, as indicated in Table 11.

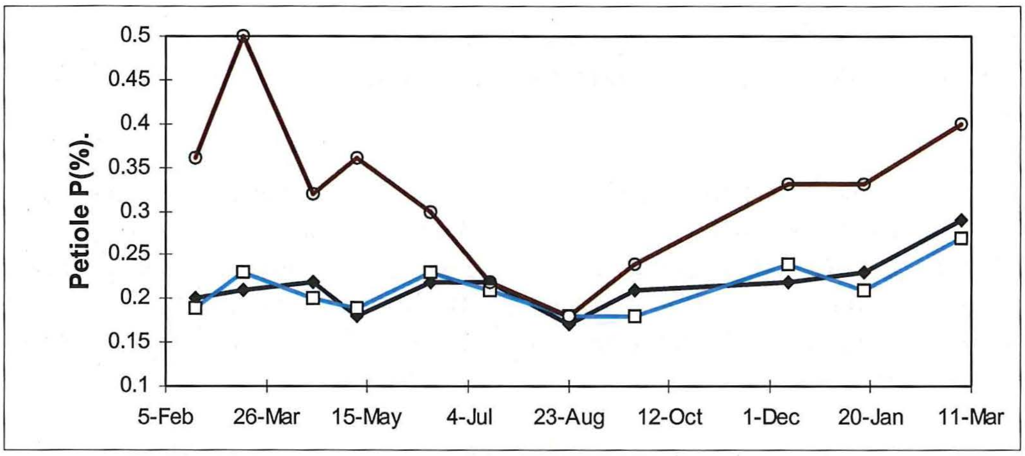
Table 11. Preliminary papaya adequate concentrations based on growth stages for N and K, based on N3K2 trends.

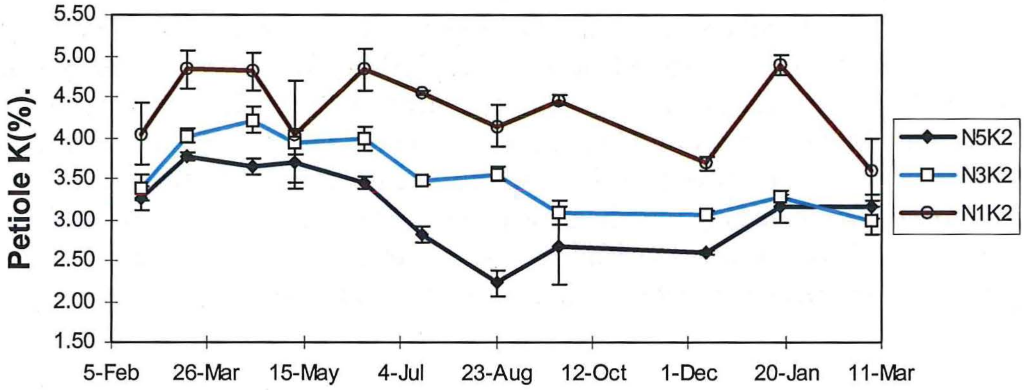
Growth stage	Petiole N %	Petiole K %
Flowering onset	0.9	3.5
Harvest start	1.1 -1.2	4 -4.2
Harvest plus 2 months	1.6 – 1.7	4 - 4.2
Harvest plus 6 months	1.1 –1.2	3.5 -4

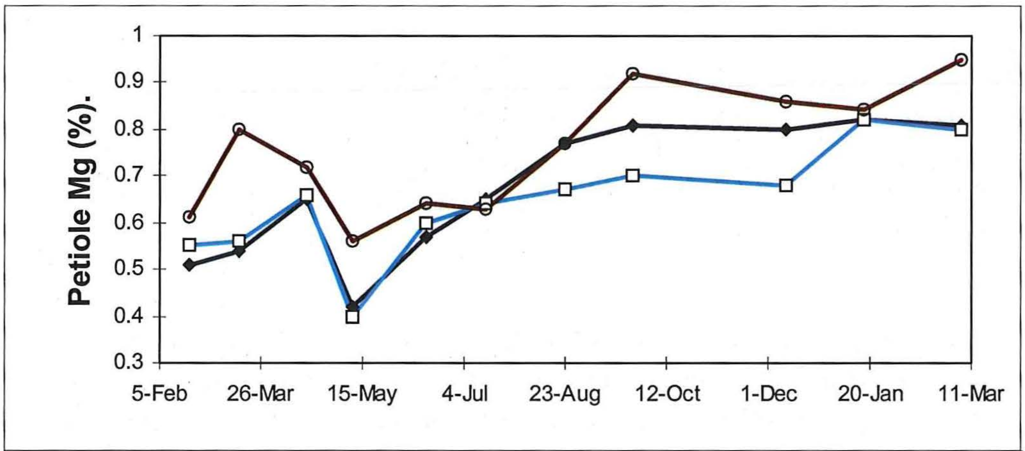
Data for N3K3 in May and September 1996 are in agreement with the trends of N3K2 in Table 11. The values in Table 11 are higher than those obtained with Cate-Nelson plots (section 3.3.5) but offer more scope for usage as they cover a wider range of plant stages. The values obtained with Cate- Nelson are more relevant to later harvest stages ie harvest plus 6 months.

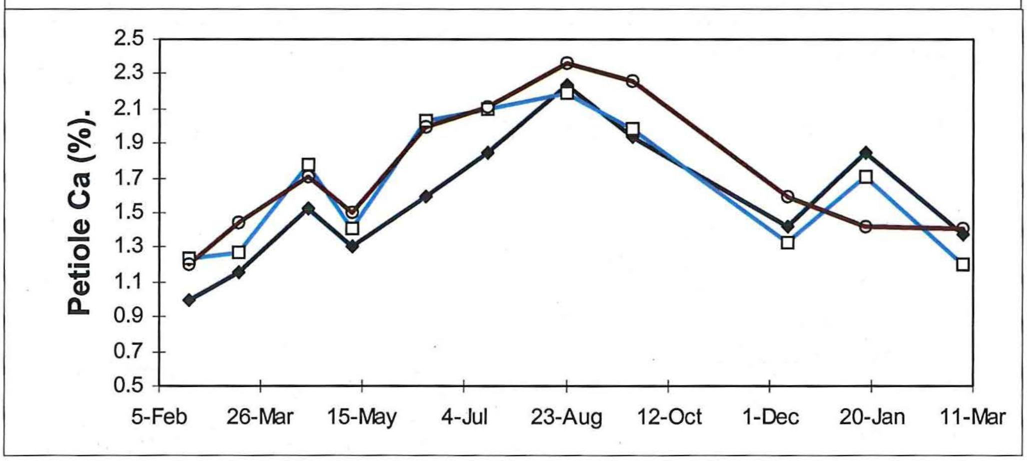
Figure 14. Changes in (a) N, (b) P, (c) K, (d) Mg and (e) Ca concentrations in petioles




Petiole P(%).
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
5-Feb 26-Mar 15-May 4-Jul 23-Aug 12-Oct 1-Dec 20-Jan 11-Mar


Petiole K(%).
5.50
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
5-Feb 26-Mar 15-May 4-Jul 23-Aug 12-Oct 1-Dec 20-Jan 11-Mar
N5K2
N3K2
N1K2


Petiole Mg (%).
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
5-Feb 26-Mar 15-May 4-Jul 23-Aug 12-Oct 1-Dec 20-Jan 11-Mar


Petiole Ca (%).
2.5
2.3
2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
5-Feb 26-Mar 15-May 4-Jul 23-Aug 12-Oct 1-Dec 20-Jan 11-Mar

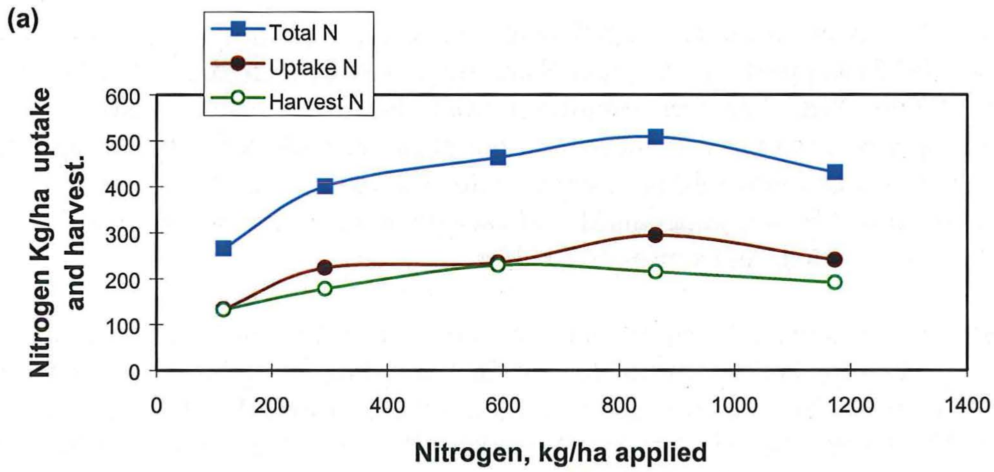
10.3.7 YIELD AND FRUIT SIZE REGRESSION ANALYSIS

The absence of strong clear relationships of yield with N and K concentrations and levels, as measured by multiple step-wise regression made this analysis difficult to interpret. Yield was found to be related (R^2 =0.91) to TCA (trunk cross-sectional area), soil pH and exchangeable soil Mg, whilst TCA was weakly related to petiole K% only, in March (R^2 = 0.32). Fruit size did not vary greatly and was not explained by any combination of variables. The negative effect of exchangeable Mg on yield may be related to lower K levels at higher Mg levels as shown in Table 10. Non-linear regressions of mean yield on March petiole sap nitrate N of R^2=0.54 and relative yield on March soil nitrate N of R^2 =0.58 were the only other relationships of significance measured. The combination of TCA and petiole sap nitrate N (RQFlex) together explained 74% of yield variation in a more meaningful manner than the model with TCA, soil pH and Mg.

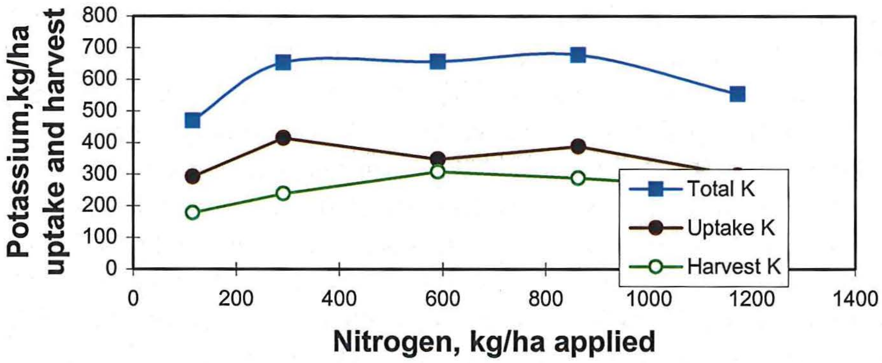
10.3.8 NUTRIENT UPTAKE AND REMOVAL IN RELATION TO APPLIED NUTRIENTS

Amounts of nitrogen uptake and harvested removal over 21 months for the five rates of N studied (Figure 15 a) indicate a peak of 507 kg/ha at the N4 rate and 265 kg/ha at the N1 rate. For mature plants the harvested N proportion of Total N uptake and removal is on average about half, and illustrates the effects of intensive and sustained high production levels. For K, (Figure 15 b) peak uptake and removal was 650kg/ha in comparison to applied 574 kg/ha over the 21 month period, with a minium of 460 kg/ha. The harvested K fraction was smaller than the uptake fraction but >200 kg/ha on average. The importance of K ahead of N in terms of both uptake and cropping requirements is suggested from these results, and the data discussed later in reference to nutrient balance models.

Figure 15 Uptake and fruit removal (kg/ha) in response to applied N for (a) N and (b) K.



(b)



10.3.9 NITROGEN AND POTASSIUM EFFICIENCY RATIOS AND BALANCE STUDIES

The ability of soil to mineralise N is difficult to gauge and is influenced by many factors. This makes accurate N balance studies difficult unless highly detailed and elaborate studies of N transformations in the soil are undertaken. Table 12 is thus a very rough estimate only, based on several large assumptions. Campbell *et al.* (1995) state that only 1-2% of the several thousand kgs of N per hectare of fertile soil is actually available to crops grown annually. The upper value of 2% was applied to Table 12 using pre and post trial levels of total soil N. Sowers *et al.*(1994) developed efficiency ratios to describe aspects of N uptake and usage as below:

- N use efficiency = G_w / N_s = crop weight/ supply of N (pre- plant soil N +fertiliser applied N + mineralised N)
- N uptake efficiency = N_t / N_s = total plant N at maturity/ supply of N
- N utilisation efficiency = G_w / N_t = crop weight/ total plant N
- Available N uptake efficiency = N_t / N_{av} = total plan N/ (total plant N + soil N at maturity)

Mineralised N was estimated as the difference between pre-plant inorganic N (2% of total N Dec 1995) and post harvest plant N and soil available N in March 1997 for the N1 plots. Fertiliser applied was subtracted from this to estimate a zero N plot. Nitrogen supply was estimated as the sum of pre-plant available N fertiliser N applied as rates N1 to N5, and mineralised N as estimated above. Total soil N (mean 0.15%) was used assuming 2% was mineralised, and each plant had a soil volume of effective roots of 0.6 cubic metres, and a mass of 756 kgs.

Available N was estimated based on total plant nutrient contents at N1 to N5 fertiliser rates at final sampling and soil available N at final sampling, using both ammonium N and nitrate N data. Using the efficiency relationships, data from Fig 15, yield means for N1 to N5 treatments, soil data for December 1995 and after final sampling and harvest in March 1997, a table of efficiencies was calculated as Table 12.

Table 12: Nitrogen use efficiencies for papaya production, per plant basis.

	Fert N kg/plant	G_w kgs	N_s kgs	N_t kgs	N_s kgs	N_{av} kgs	G_w / N_s	N_t / N_s	G_w / N_t	N_t / N_{av}
N1	0.07	55	0.182	0.177	0.005	0.184	301	0.97	310	0.969
N2	0.177	76.1	0.289	0.266	0.032	0.298	263	0.920	286	0.893
N3	0.358	75.2	0.47	0.308	0.047	0.355	160	0.655	244	0.897
N4	0.523	74.8	0.635	0.338	0.137	0.475	118	0.532	221	0.712
N5	0.711	74.7	0.823	0.287	0.216	0.503	91	0.349	260	0.571

Nitrogen use efficiency, N uptake efficiency, N utilisation efficiency and N available uptake efficiency were maximum at the lowest rates of N applied and decreased as N applied increased. High rates of applied N at rates of N2 or higher appear to be inefficient and wasteful. Since N2 rates and higher gave similar yields, there is a strong case to use the N2 rates as the preferred rate of N in this soil type. It is not possible to do a similar analysis of potassium efficiency of usage due to limitations in data; however, based on mean yields across N rates estimates of K use are as follows:

K1 = 1162, K2 = 368, K3 = 222, K4 = 138

Where K efficiency is defined as crop weight Kg / soil supply of K Kg

This pattern reflects that found for N efficiency data: The higher the application rate the lower the efficiency of usage.

An attempt was made to audit both N and K via nutrient balance models (Tables 13,14). Data was used from yield data, fertilisers applied (Table 7), soil analysis data (Tables 6,10 and untabulated data), together with destructive data of chapter 5.

The assumptions made with respect to Tables 12,13 and 14 are:

Volume soil / plant is 0.6 cubic metres; mass is 756 kgs; root depth is 20 cm (containing 78% of active roots); mass soil / hectare is 1255 tonnes,

Table 13 . Nitrogen balance sheet per plant basis, Oct 1995 to March 1997:

	N1	**N2**	**N3**	**N4**	**N5**
Total soil N %	0.17	0.13	0.15	0.145	0.145
Est.Soil reserves avail N at Dec 1995, g	25.7	19.6	22.7	22	22
N applied g/plant	70	177	358	523	711
N reserves + applied	96	197	381	545	733
Plant uptake and harvest loss, g	177	266	308	338	287
N reserves +applied -uptake -harvest, g	-82	-69	73	207	446
Soil nitrate N Mar 97 mg/kg	4.5	40	55	122	159
Soil avail NH_4 N Mar 97 mg/kg	2.7	3.9	7	59	127
Total Soil avail N reserves Mar 97	5.5	32	47	137	216
N unaccounted for g/plant	86.8	101	-25.7	-70	-230
N unaccounted for kg/ha	144	167	-42.6	-116	-382

area of planting strips =57% of 1 hectare, depth of roots 20 cm, BD = 1260kg/m^3, mass soil = 1436.4 tonnes, 0-20 cm sample includes most of the roots

The above audit sheet for nitrogen shows that N1 and N2 treatments had deficit N budgets. These deficits result from apparent mineralisation of total soil N to supply uptake and harvest demands in excess of applied N and N reserves, and thus serve as an indication of the rate of mineralisation of N over the period of 21 months. Treatments N3, N4 and N5 all had surplus budgets of N, indicating a movement of N out of the 20 cm zone or assimilation back into the total N pool. N unaccounted for at the trial completion was 87 and 101 g/tree for N1 and N2 respectively, indicating a possible level N mineralisation. Since the model of Table 13 assumes 2% N mineralisation rate per annum, the data cannot be confirmed but will be useful as a first estimate. It is apparent that the favoured "safe" application rate of N will lie close to the N2 rate of 292 kg/ha total for 21 months in this soil, for similar conditions.

Table 14. Potassium balance sheet

	N1	N2	N3	N4	N5
Soil exch K at start mg/kg	148*	148	148	148	148
Soil reserves at start g/plant	112	112	112	112	112
K applied g/plant (K3 rate)	348	348	348	348	348
K applied plus reserves g/plant	460	460	460	460	460
Plant uptake g/plant	182	259	217	243	186
Harvest removal plus plant uptake g/plant	294	408	410	423	347
(K Applied +reserves) -total plant uptake and removal	166	42	40	27	113
Soil reserves at end g/plant	386	309	165	187	147
Soil exch. K. at end mg/kg	512	410	219	246	195
K unaccounted for g/plant	-220	-267	-205	-159	-250

*0.38 meq/100g

Table 14 shows that for K3 rates of application 159 to 267 g/plant of soil available K was released from the labile pool of soil K. The K audit suggests that significant amounts of K were released from fixed K pool to labile K particularly at higher pH as found with N1. Rates of K application above the K3 rate studied herein are likely to be wasteful in this soil as the soil is readily able to supply additional K and the K3 rate together with reserves at the start exceeded all plant requirements. Starting with 213 kg/ha of K available and the requirement of 657 kg/ha total over 21 months then the maximum required application would be 444 kg/ha total, not allowing for additional K released from fixed sources. This rate would be intermediate of the K2 and K3 rates for this soil.

10.4 DISCUSSION

A wide range of applied nitrogen fertiliser rates had no effect on papaya fruit size and quality. Highest rates of N gave the thinnest plants (stem girth) but there was little difference in plant height at maturity across N rates. High rates of applied N and K were associated with higher electrolytic conductivity's, low pH and low available Ca levels in the soil. All treatments showed substantial to large declines in available Ca over the study, and this effect on yield and fruit quality was not studied. Soil pH did not decline much from the initial low levels of 4.7 and actually increased in the N1, N2 and N3 plots over the period.

The uptake of N and removal as harvested fruit increased up to the N4 rate, then declined, while K uptake and removal was higher at K2 and K3 rates, declining with K4 rates. Efficiency of N usage as established by 4 ratios, showed that N1 and N2 rates gave the most efficient N usage and uptake. At higher rates (N5) the ratios declined markedly suggesting that at application rates exceeding 500 kg/ha of applied N, would be wasteful in this soil type. The N balance audit confirmed this showing that at N1 and N2 rates of application apparently there was adequate N mineralisation to supply deficits for plant uptake and fruiting. The assumed mineralisation rate of 2% was not tested in this study, thus such balance study data are not conclusive.

Yields were significantly higher at the N2 to N5 rates, with N3K3 giving the highest yield of 141 tonnes per hectare equivalent. The lowest yields were obtained with N1 rates and N1K4 gave the lowest overall yield of 79 tonnes per hectare. Averaged over N rates the K3 rate gave the highest yield, significantly higher than both K1 and K2 but not K4. Yield data suggest that somewhere between 292 and 591 kg/ha of N and 574 kg/ha of K (350 g/tree) is required over 13 months for superior yields.

Nitrogen efficiency and balance studies showed that N1 and N2 rates of application minimse nutrient losses and maximise nutrient efficiencies, compared with N3, N4 and N5 rates of application. Given that N2 yields over K rates were not significantly different from N3, N4 and N5, and that N2 K3 resulted in 109 tonnes per hectare, then the N2 rate of application of 292 kg/ha over 13 months is preferred and should be economically efficient also. This is equivalent to 176 g/tree of N.

Surveys in Queensland (Richards *et al.* 1995) established that growers were commonly applying 300 to 1100 kg/ha per 2 years of N and 400 to 1400 kg/ha of K. Awada (1969) found highest papaya yields of 96 kg/tree at 1000g/tree of N (equivalent to >1500 kg/ha) for a 2 year period. Reddy *et al.* (1986) established highest papaya yields at 155 tonnes per hectare for an application of 250g/tree of N and 225 g/tree of K over 2 years. Awada and Long (1971a) reported that 630 g K per tree per year was required to achieve critical K concentrations in petioles and leaves. Purohit (1977) reported highest papaya yields of 161 tonnes per hectare by applying 250 g of N and 415 g K per tree over 18 months. The data of Awada favours higher fertiliser usage, whereas other authors report lower requirements in line with this paper. Actual field application rates will vary with soil type and method of placement. The scope to reduce applications by using fertigation is very promising, and may also result in reduced leaching losses.

Establishing critical concentrations as a guide to nutrient management was not successfully achieved in this study. Adequate standards were however defined. Bowen (1992) derived adequacy concentrations ranges of 1.37 - 1.46% N, 0.194 to 0.208 % P, 2.92 to 3.11% K, 0.24 5 ca and 0.56% Mg in petioles from healthy plants. Awada and Long (1971a), in Hawaii established critical N in petioles at 1.14 to 1.28%, equivalent to 800 mg/kg of nitrate N, and critical K at 3.65 % (1971b). The critical P of 0.21% in petioles was established by Awada and Long (1969). Reddy *et al.* (1986) measured a range of concentrations in petioles as found in Table 15. Optimal soil pH was set at 5.5 to 6.7 in Hawaii by Awada *et al.* (1975). In Australia, Robinson (1986) reported adequate N as 1.3 to 2.5%, P as 0.2 to 0.4%, K as 3 to 6 %, Ca 1 to 2.5% and Mg 0.5 to 1.5%. Such data as discussed herein is presented in Table 15.

Using the results of this trial it is suggested that critical N and K be modified according to growth stages at sampling times, from flowering onset through to late harvest as shown in Table 11, for recently matured petioles.

The results of Table 11 generally compare with the range of data of Table 15 for N and K, the values obtained by Bowen were lower and those of Reddy *et al.* higher than, the reported values of Table 15. Table 11 data also are similar to survey results of growers in Queensland (Richards *et al.* 1995).

The lack of reliable relationships between soil levels and yield and leaf concentrations and yield of papaya does not allow detailed study. However, recommendations were made on adequate concentrations and levels of nutrients such that for petioles the adequate range dependent upon plant age after flowering commenced would be 0.9 to 1.6%, nitrate N 19\680 mg/k and K, 3.5 to 4.2%. For the soil type studied minimum available N would be 30mg/kg, and exchangeable K 0.6 to 0.85 cmol(+)/kg.

CHAPTER 11: THE UTILITY OF QUICK TEST METHODS TO ASSESS PAPAYA NUTRIENT STATUS.

11.1 INTRODUCTION

Quick test methods to assess plant nutrient status are a departure from the traditional laboratory based procedures, offering quick results using reliable and easy to use equipment, in the 'field'. Most quick tests are done using sap samples from quick growing crops such as cereals, vegetables and fast growing fruits. Papaya plants are neither short lived annuals nor long living perennials, and thus quick test methods have the potential to be useful over the 20 to 30 months of commercial crops.
Handson and Shelley (1993) made the following assessment of quick test sap analysis:

- technique most suited for N, P, K and S
- petioles of youngest mature leaves or stem base (cereals) are used as index tissue
- limitation of sap concentrations dependent upon plant and soil moisture status
- sap analysis best as monitoring tool; use trend data rather than individual point sampling
- results from meters are reliable and accurate

Treatments from the Nutrition trial were used to evaluate sap analysis against laboratory analysis, monitor trends and to relate sap data to final yields. Soil nitrate N data were also compared with a meter against laboratory measurements and with final yield data, in an attempt to evaluate a particular meter for quick test analysis. The requirements for papaya petiole sampling in terms of sample size and replicates were investigated.

11.2 METHODS AND MATERIALS

11.2.1 PLANTS

From February to August 1996 treatments N1K3, N3K3 and N5K3 from the papaya nutrition trial were sampled for petioles (see methods 3.1) by collecting 3 petioles from each plot of the treatments. Petioles were washed in detergent, ground in a processor and 15g material (weighed to 3 places) collected and boiled for about 5 minutes in 50ml distilled water. When cooled the solution was filtered and transferred to a 100 ml cylinder (+/- 1ml) and made up to 100 ml volume. This solution was then tested with a Merck Ltd. RQflex reflectometer and Merck reflectoquant test strips, to measure nutrient concentrations. Test strips used included Nitrate 5- 225 mg/L, Potassium 0.25-1.20 g/L and phosphate 5 -120 mg/L, and test instructions followed. From solution concentrations in mg/L petiole concentrations in mg/kg were determined with the formula below:

mg/kg (dry wt basis) = mg/L *Vol. Water (ml)/ dry weight sample, g.

Moisture content of petioles was determined by oven drying at 75 ^{o}C for 2 days.
From October 1996 to March 1997 the sample preparation was modified to focus on simpler petiole sap analysis. For this 3 petioles from each treatment plot sampled were washed, ground wet then a sub-sample crushed in a stainless steel, garlic crusher to collect 2.0 ml of sap by pipette. This sap was diluted with 8.0 ml distilled water to a

final volume of 10 ml. The final concentration in mg/L was obtained by multiplying measured value times 5

11.2.2 Soils

For soils only nitrate could be measured and this was done by shaking 10g soil with 50ml water for 30 minutes, then centrifuging and filtering of the supernatant. The solution was then tested for nitrate using test strips and procedure as described above. Moisture content of each sample was determined by oven drying at 105 °C for 2 days. Measured mg/L nitrate N was adjusted for volume of water and mass of oven dry soil to calculate mg/kg of nitrate N.

11.2.3 Sample variation

In order to establish correct sample size for commercial usage of the technique, a commercial farm was sampled in September 1997 near Innisfail. A total of 90 petioles were collected (index position) from 800 mature papaya plants, and random samples of 3, 5 and 10 petioles per sample were drawn, ground and analysed for sap nitrate, phosphate and potassium. For sap nitrate, 3 readings per sample were taken to assess within sample variation.

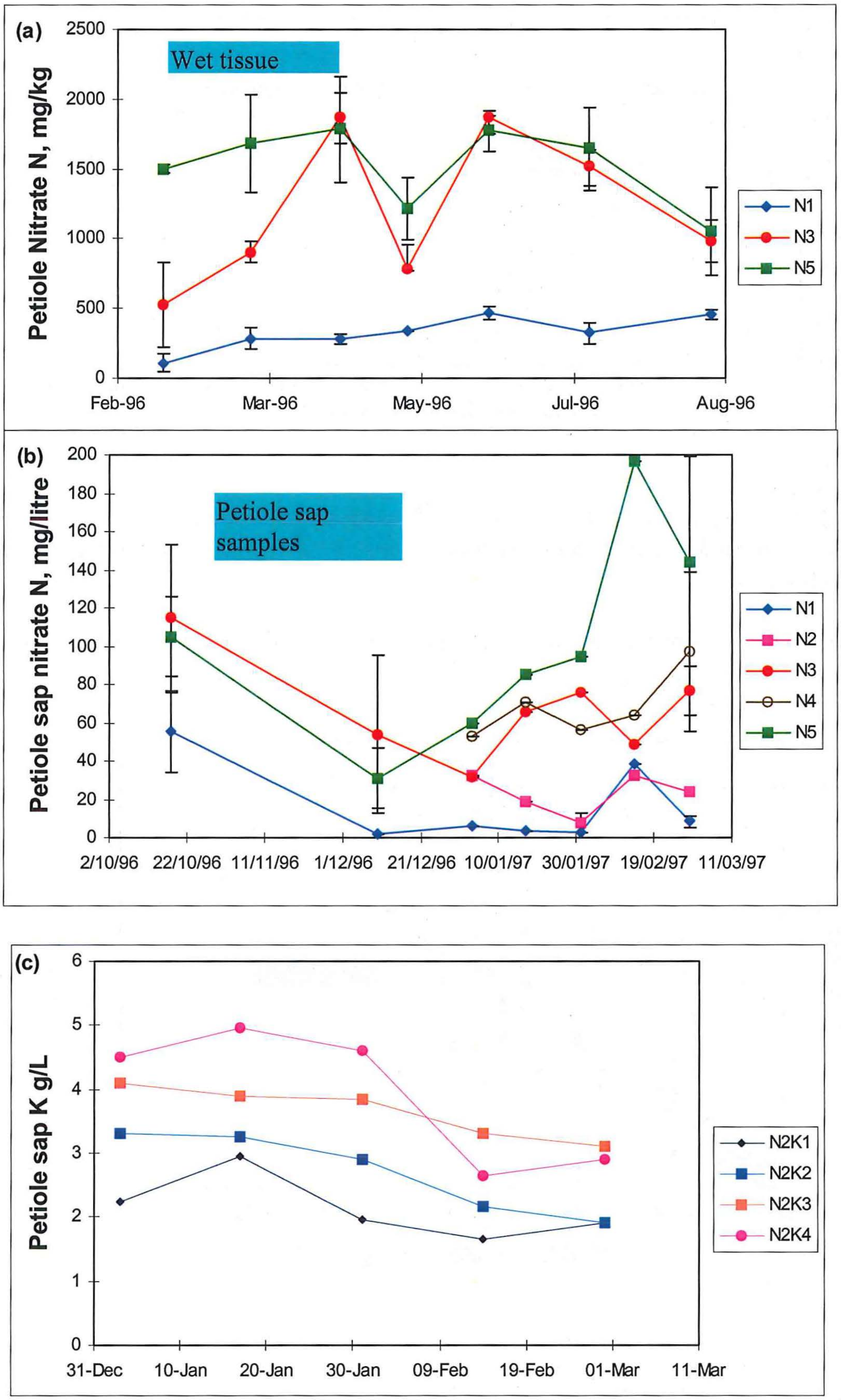
11.3 Results

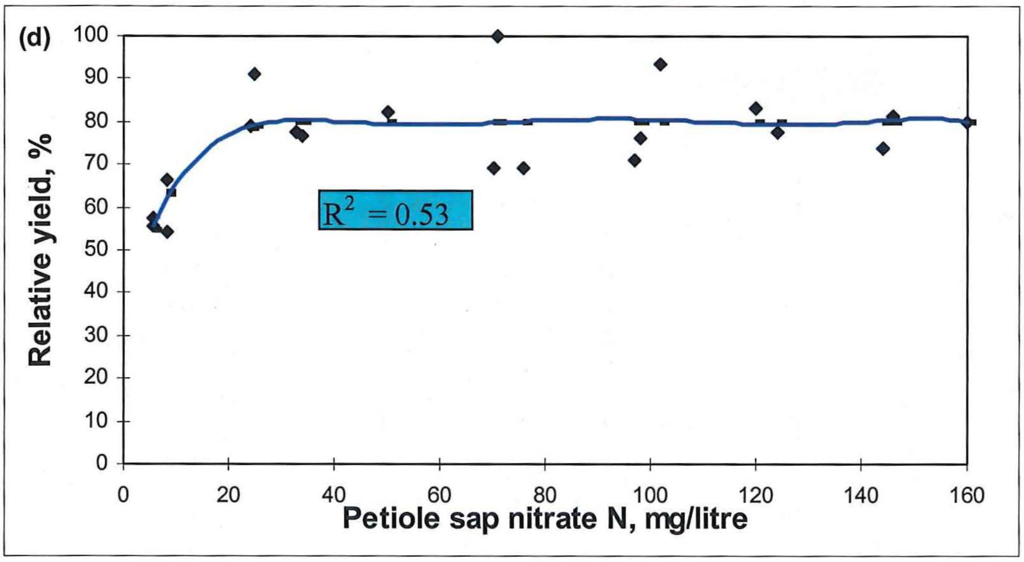
11.3.1 Plants

The plots of wet tissue analysis (Fig. 16(a)) shows the consistently lower concentrations of N1 treatment plots than both N3 and particularly N5. The se (standard error) bars show significant differences arising from the treatments of applied N fertilisers. The sap nitrate data (Fig. 16(b)) indicates mostly significant differences between N1 and N5 plots, although se's are comparatively larger than for the wet tissue samples. There was a 5 fold increase in nitrate N of sap in N5 treatments compared to N1 treatments at the conclusion of the trial in March 1997. Sap K concentrations (Fig. 16c) were consistent across treatments and reflected the variable K fertiliser applications in the trial.

Petiole sap nitrate N was quite well related to final yield in March 1997, with an R^2 =0.53 (Fig. 16(d)) and indicates an adequate spa nitrate N (RQflex) of 35 mg/L which equates to 1680 mg/kg nitrate (Fig 17 (a)). From Chapter 3 and using the equations developed herein, adequate K and P concentrations in plant sap would be approximately 2.4 g/L and 118 mg/L, respectively.

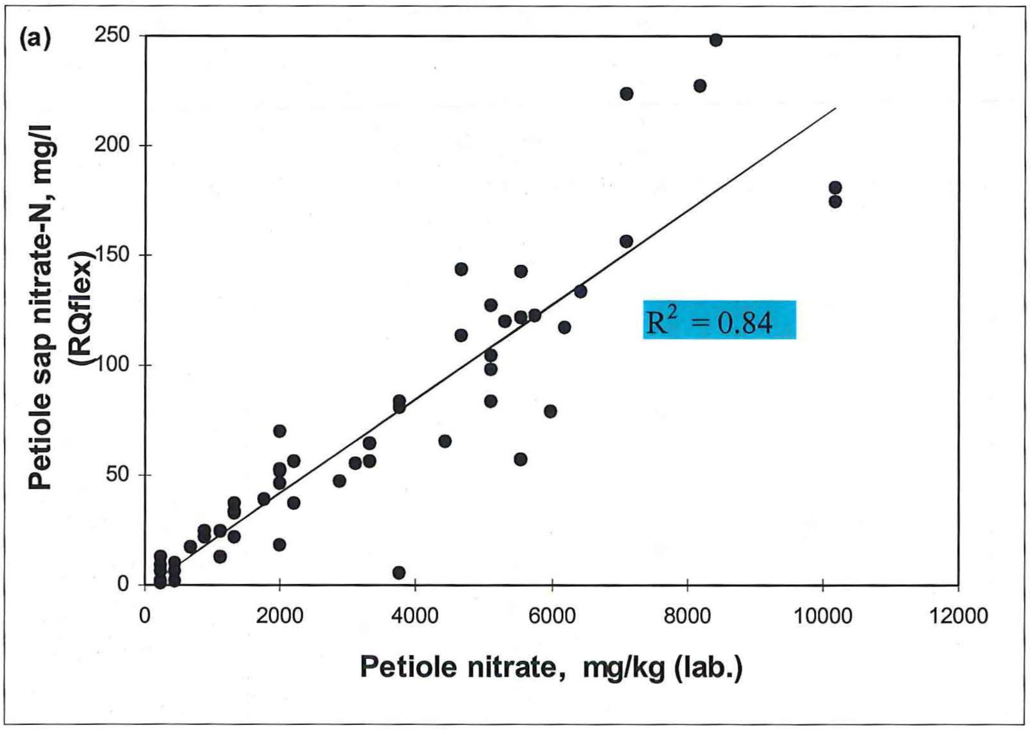
Figure 16. RQFlex reflectometer data for (a) nitrate N petiole wet digest , (b) Nitrate N petiole sap analysis (c) petiole sap K and (d) relationships with papaya relative yields(March 1997 data).

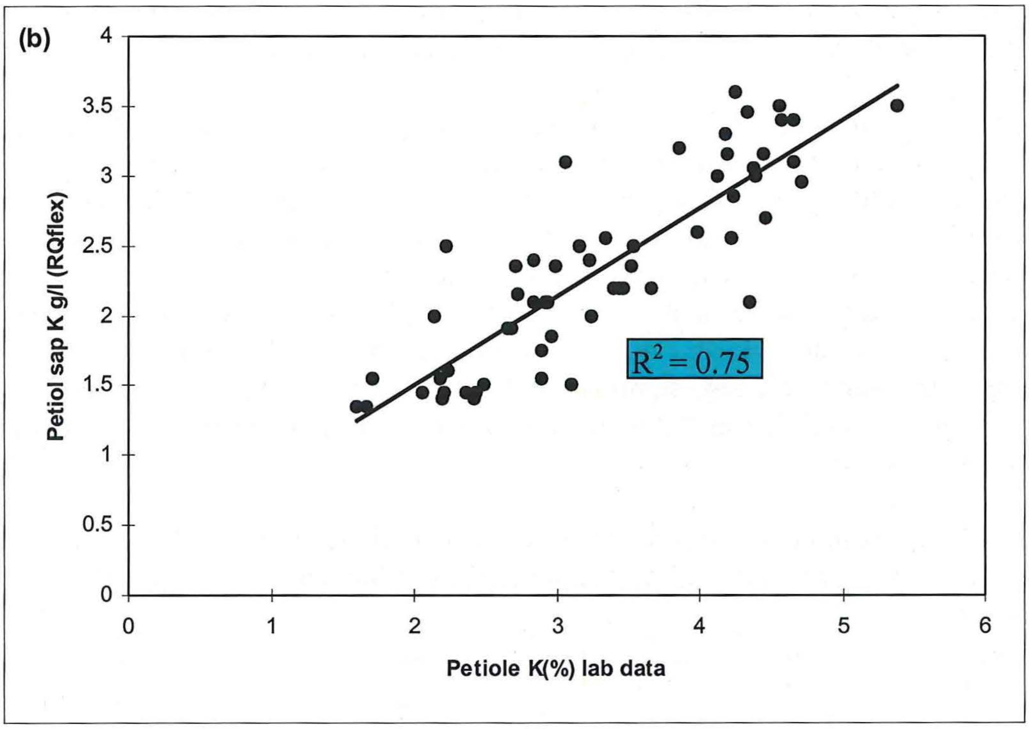

(a)
Wet tissue
Petiole Nitrate N, mg/kg
2500
2000
1500
1000
500
0
Feb-96
Mar-96
May-96
Jul-96
Aug-96
N1
N3
N5
(b)
Petiole sap samples
Petiole sap nitrate N, mg/litre
200
180
160
140
120
100
80
60
40
20
0
2/10/96
22/10/96
11/11/96
1/12/96
21/12/96
10/01/97
30/01/97
19/02/97
11/03/97
N1
N2
N3
N4
N5
(c)
Petiole sap K g/L
6
5
4
3
2
1
0
31-Dec
10-Jan
20-Jan
30-Jan
09-Feb
19-Feb
01-Mar
11-Mar
N2K1
N2K2
N2K3
N2K4

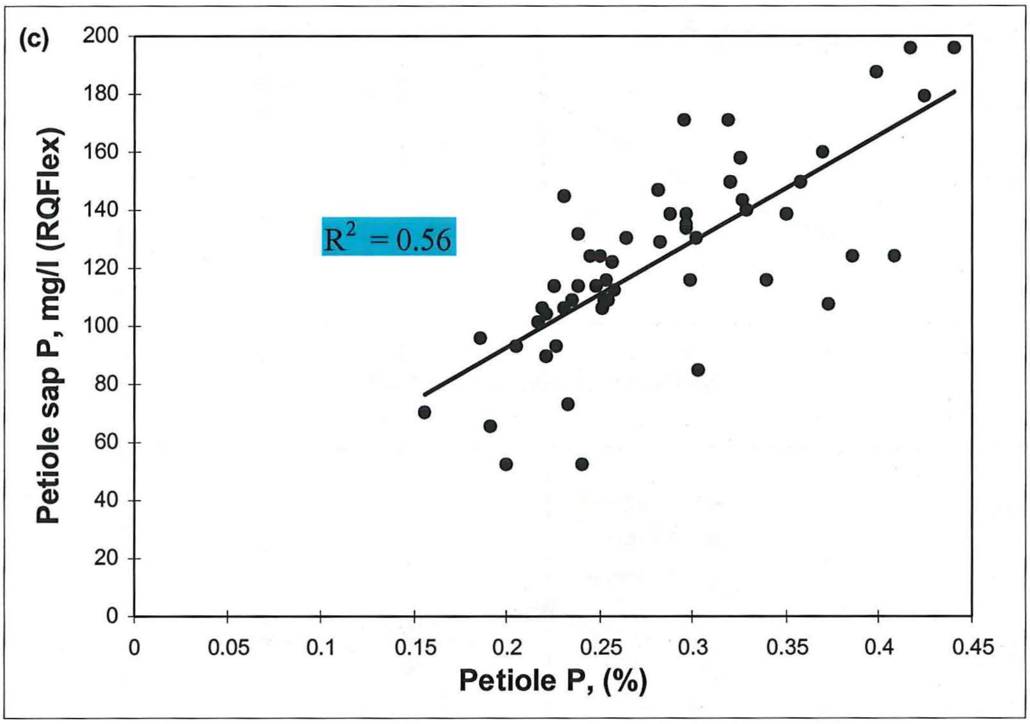


Regressions of sap nitrate N, P and K with corresponding petiole digests in the laboratory (method) revealed some useful relationships as indicated in Figures 17 (a), (b) and (c).

Figure 17. Regressions of petiole sap concentrations with laboratory data for (a) Nitrate N, (b) K and (c) P.







The appropriate equations describing the conversion of measured Nitrate, P or K in mg/L to mg/kg or % are as below:

Nitrate mg/kg = (sap nitrate N, mg/L +0.917)/0.0214

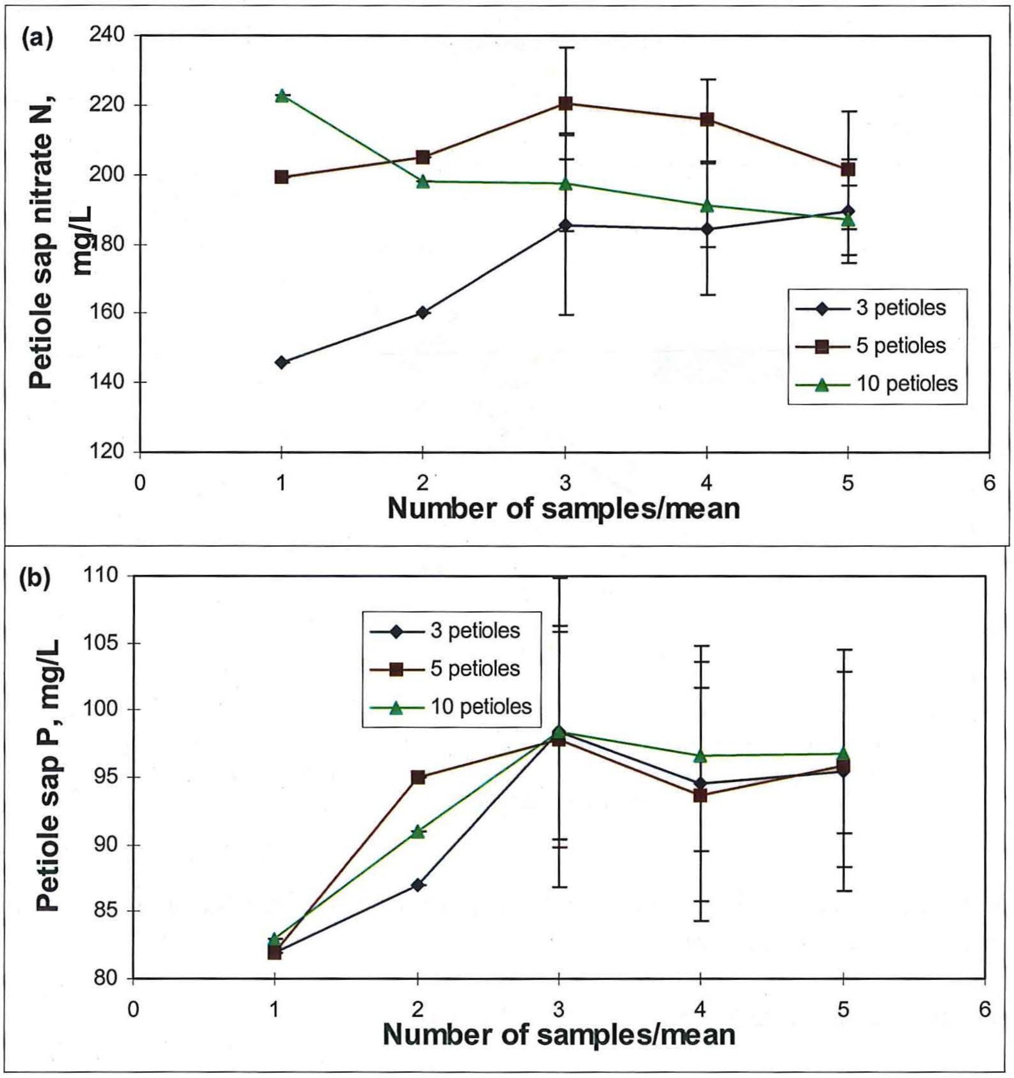
P (%) = (sap P mg/L-19.8)/365.2

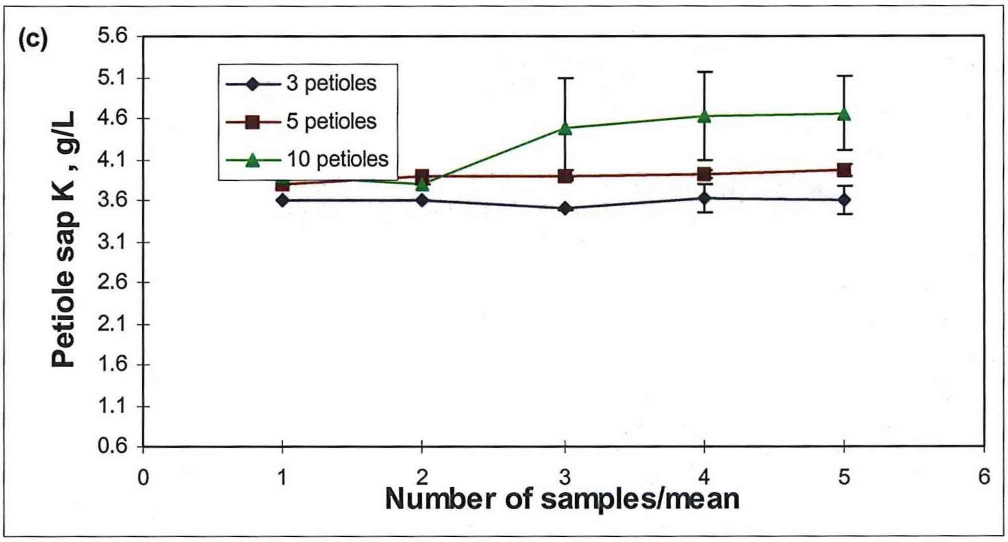
K (%) = (sap K g/L -0.22)/0.63

The relationships involving nitrate and K are particularly useful in assessing plant nutrient status with time and in relation to adequacy levels (Chapter 3).

Petiole sampling analysis requirements in terms of sample size and number of samples to collect per mean sample were assessed by gauging the effect of these variables on the mean value and its variability (standard error and CV%). The results for sampling requirements for papaya petiole sap analysis revealed that for nitrate N and K the use of 3 petiole samples was associated with lower concentrations (Fig 18) for 3 or fewer samples per mean. Five and 10 petioles sample sizes gave similar mean concentrations regardless of the number of samples averaged together. For K, 5 petiole sample means were also significantly lower than were 10 petiole means for 3 or more replicates. Petiole sap P did not show a lot of variation regardless of sample size and replicate number.

Figure 18 Changes in petiole sap N, P and K concentrations with sample size (3,5,10 petioles per sample) and number of sample replicates bulked (1 to 5 samples). SE bars shown.

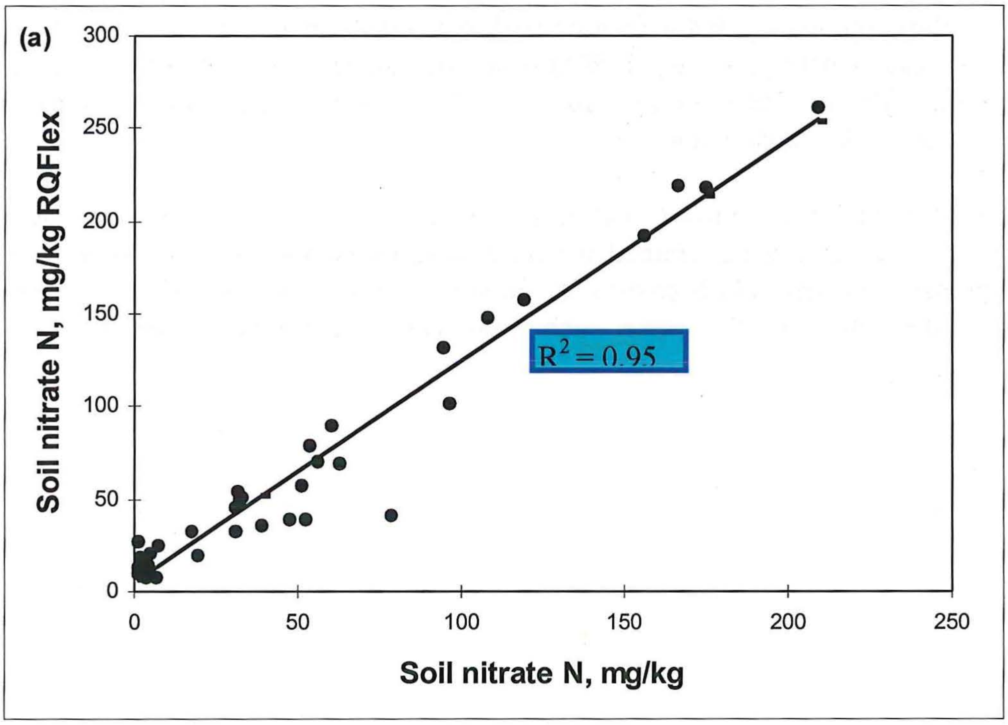


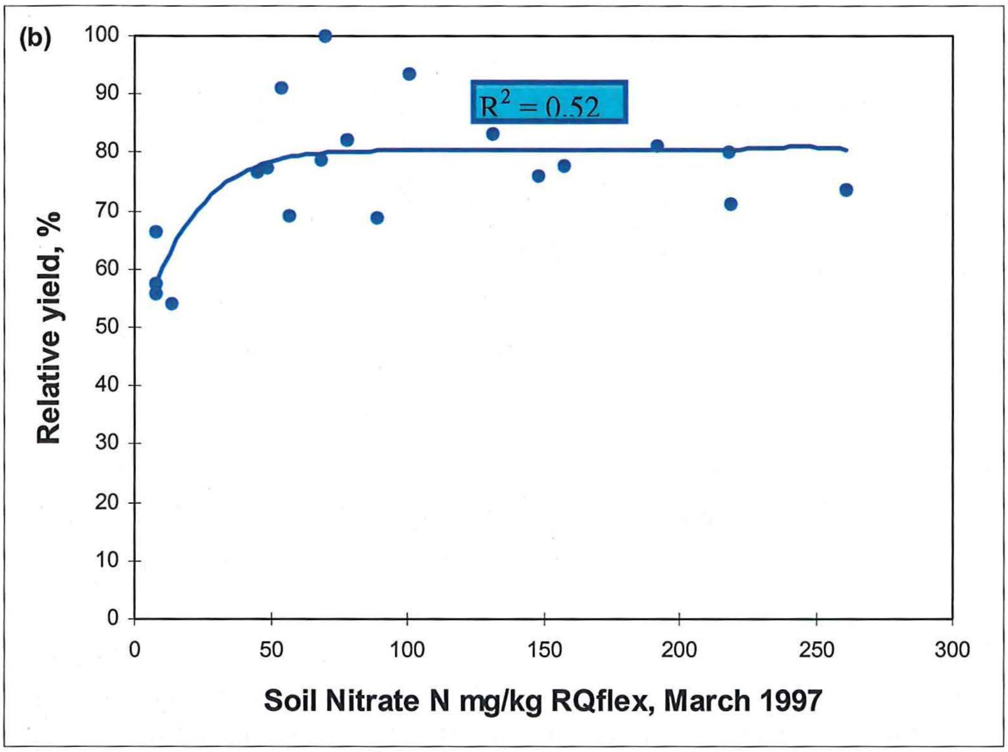


11.3.2 SOILS

Figure 19(a) shows the excellent regression obtained with RQFlex measured nitrate N and laboratory measured nitrate N, for soil samples combined from July 1996 and March 1997. The accuracy of the RQflex method is thus established. The relationship of relative papaya yields (100%= N3K3) with soil nitrate N (RQflex) established a useful R^2 =0.52, and indicates an adequate soil nitrate N of 40 mg/kg.(See earlier comments on this issue)

Figure 19. The regression of (a) soil nitrate N RQFlex and laboratory nitrate N and (b) RQFlex soil nitrate N and relative yield.





11.4 Discussion and Conclusions

Good relationships of petiole sap nitrate N, sap K with laboratory data, the sensitivity to detect differences in fertiliser applications and reasonable yield relationships (N only) have established the potential for using reflectometers to monitor N and K plant nutrient status, and obtain possible indications with P status. The sampling requirement data established that standard errors across sample means were not high and would allow the use of this technique with reasonable precision, although small sample sizes less than 15 petioles per hectare run the risk of measuring lower nutrient concentrations. The preferred sample size would be 10 petioles, with 3 replicates collected to establish a mean value.

The adequate level for soil nitrate N RQFlex was determined as 40 mg/kg and was well related to laboratory determined nitrate and reflected the range of applied N fertiliser across treatments but because individual applications of N fertiliser has a big impact on soil nitrate levels this makes such monitoring very difficult to utilise.

CHAPTER 12: BIOMASS, GROWTH AND NUTRIENT CONTENT OF PAPAYA, AS A GUIDE TO FERTILISER APPLICATION.

12.1 INTRODUCTION

Over-fertilisation particularly with N is often associated or implicated with high levels of soil nutrients, soil nutrient imbalances and pH problems, imbalances in plant growth and reproductive activities, fruit quality issues, leaching of N and K in irrigation or rainwaters, excessive vegetative growth and vigour. Weinbaum *et al.*(1992) concluded that this problem is widespread in horticulture and is supported by a number of factors including the lack of integration of soil water and nutrient management; lack of allowance of non-fertiliser sources in determining plant fertiliser needs ; insensitivity of foliar analysis to over-fertilisation. In Horticulture farming systems, high levels of inputs are needed to produce the high value and high quality produce outputs, and fertiliser costs are often a small overall cost, in relation to harvesting, processing and marketing. This does not give financial incentive to many growers to become better nutrition managers. There is also often a linkage between commercial advisory services and suppliers of fertilisers, and this raises doubts about the quality of such advice.

Fertiliser usage in papaya in north Queensland is very high as established by industry survey (Richards *et al.* 1995) and given the very high rainfall and large irrigation applications in drier times, the sustainability and validity of such practices needs to be assessed. This was done by reference to sequential destructive sampling of papaya plants growing in a nutrition trial in north Queensland.

12.2 METHODS AND MATERIALS

12.2.1 TRIAL DETAILS

Plants growing at South Johnstone Research Station plots, of hybrid varieties IB and IE (1666 plants/ha) were used to study changes in whole plant biomass and nutrient content from January 1996 to May 1997. Details of sampling are recorded as Table 13. Plants were sampled from the papaya Nutrition Trial using guard plants (up to age 8 months) and from treatments N1k3, N2k3, N3k3, N4k3 and N5K3 at age 21 months. Plants at age of 15 months were sampled from an earlier trial using variety IE, closely related to 1B. Ages include 2 months of nursery time thus are measured from nursery sowing. All plants were irrigated with under tree micro sprinklers, scheduled via neutron probe recording. Meteorological data from January 1996 to March 1997 are shown as Figure 20.Fertiliser to guards was based upon N2 K2 rates and rates of application are listed below, and fertilisers were split over monthly applications as identified in Chapter 3.

Figure 20. Meteorological data for South Johnstone Research Station, 1996/1997.

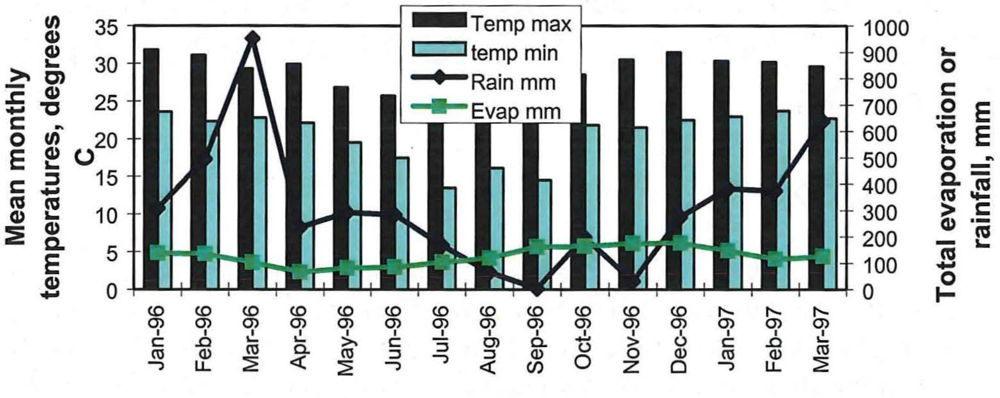


Table 15. Sampling dates, plant numbers, samples collected and nutrient sampling methods for destructive sampling of papaya.

Sampling date	Plant age months	Number of plants	Source of plants	Method of nutrient sampling
Oct 1996	2	6	Nursery	nil
Nov 1996	3.5	6	Nursery	bulked samples
Dec 1996	5	6	Nutrition trial	bulked samples
Jan 1997	6	5	"	bulked samples
Feb 1997	7	5	"	bulked samples
Feb 1996	8	4	"	individual samples
Jan 1996	15	4	Variety trial	individual samples
May 1997	21	15	Nutrition trial	5 N treatments, means of each treatment (3 trees)
April 1997	20	24	Irrigation trial	6 irrigation treatments, means of each (4 trees)

12.2.2 SAMPLING OF PLANT TOPS

Plants were first sampled for leaves and petioles and these were removed separately for weighing and sub-sampling for dry matter determinations. Both leaves and petioles sub samples were collected over the range from immature to old organs. Very small petioles and leaves were left attached to the crown apex. Plant parts were cut into smaller sections to assist oven drying, and for 3.5 month plants petioles and leaves were collected as one sample.

The fruit were then stripped from the tree and divided into ripe mature, green mature and green immature portions, weighed separately and sub-sampled separately, for dry matter content. Fruit portion sub-samples (as segments) were obtained over a range of fruit sizes within each section and were cut into small pieces. Fruit stalks were left attached to the stem, and flowers and buds included with green immature fruit. The crown of the stem was cut off at the point of tissue maturation, and weighed and sub-sampled (as 3cm thick transverse discs) for dry matter content, and the remaining stem was cut off about 25 cm above ground level, weighed and sub-sampled along its length for dry matter content (using 3cm thick discs).

12.2.3 Root systems sampling

For smaller trees in the field, a spade was used to trench around plants to about 50 cm radius and plants were dug and levered out of the ground. Although not all roots were removed, inspection revealed that about 90 % were on average. For larger plants (8months+) trenching at about 1m radius in combination with bunding of water around roots to saturate the soil fully was required, and plants lifted out vertically with the assistance of a tractor.

After removing root and stumps, the parts were washed down with hoses and allowed to air dry before weighing. The stump was first removed from the roots and weighed and sampled separately. No attempt was made to classify roots on size or position, but the vast majority of lateral roots were located within the top 40 cm, and taproots usually were no longer than 120 cm in length. Sub-samples were taken over the entire root system by selecting a mix of lateral and taproots of varying sizes.

For the irrigation trial, more detailed data on a few trees relating to root distribution was collected. For the nutrition trial data for 21 months root systems were not excavated due to the time constraints, and root data were estimated using results from 15 month old trees, scaled up on the basis of root/tops ratios.

12.2.4 Nutrient sampling and analysis, nutrient content

Samples used to determine dry matter content were also used for nutrient analysis. All such sub-samples collected were washed then oven dried at 70-75 $^{\circ}$ C for 48 hours, before grinding in a hammer mill. Dried ground samples were analysed at the DNR laboratories in Mareeba, north Queensland, using standard analytical procedures as outlined in Chapter 3.

After calculations of plant organ dry weights, nutrient concentrations were determined using mean or bulked organ concentrations and respective dry matter weights. Total plant nutrient contents were the sum of all plant organs for plants aged 3.5 to 7 months, based upon bulked samples for nutrient concentration determinations. For plants aged 8 months and above, individual plant nutrient contents were calculated and used to arrive at means for each age group, using individual plant samples to determine nutrient concentrations.

For 21 month aged plants, it was necessary to calculate root biomass using a root % of total dry matter (21.4%) based upon means of 5, 6, 7, 8, and 15 month old plants. Total dry matter was adjusted for each treatment of 21 month old plants accordingly from treatments N2, N3, N4, and N5. For nutrient contents of roots the mean ratios of root/tops nutrient content ratios were used from 15 month plants, to calculate nutrient contents of roots, such that N = 0.117, P =0.150, K=0.262, Ca =0.172 and Mg =0.255.

For 15 months old plants fruit analysis revealed the following trends:

Table 16. Ranges in fruit concentrations and fruit weight per plant at 15 months age.

Fruit stage	N %	P %	K %	Mg %	Ca %	Dry weight fruit /plant g
Ripe mature	1.42	0.21	2.25	0.29	0.29	598
Green mature	1.97	0.30	2.68	0.33	0.38	726
Green immature	2.31	0.36	2.80	0.46	0.63	1228

Fruit nutrient contents were based upon each mean recorded harvest weights, a mean dry matter of 8.22%, (green mature fruit) and mean green, mature fruit concentrations of 1.97%N, 0.30 %P, 2.67%k, 0.38% Ca and 0.33% Mg (Table 14). Total nutrient content as harvested loss was added to tops and roots contents to arrive at a whole plant uptake and removal figure for each nutrient and treatment, and means were calculated across treatments,

For 15 month old trees, calculations were quite straightforward with the exception of allowing for fruit on the plant at sampling time in relation to fruit to be harvested in the period 15 to 21 months. Since nutrient contents were to be examined in a time series, it was necessary to add harvest removal from age 10 (beginning of harvesting) to 15 months and to subtract nutrient storage in fruits on 15 month old plants at sampling time.

12.3 RESULTS

12.3.1 BIOMASS AND GROWTH CHANGES

Total dry weights (Fig 21) increased rapidly after 5 months age, following an exponential type of growth response, with an R^2 =0.996. The curve is described by a Gompertz function such that:

$$\text{Dry matter/tree} = 11.905 \exp(-\exp(0.1862*\text{age} + 2.116))$$

Mean monthly growth increments were 0.115kg/month up to age 6 months, 0.71kg/month from 6 to 17 months and 0.32 kg/month from 17 to 25 months. On this basis the period from beginning of flowering at about 6 months age (4-5 months field planting) through to about 17 months age is the period of maximum rates of biomass accumulation and growth.

Figure 21. The increase in papaya total plant dry weight with age

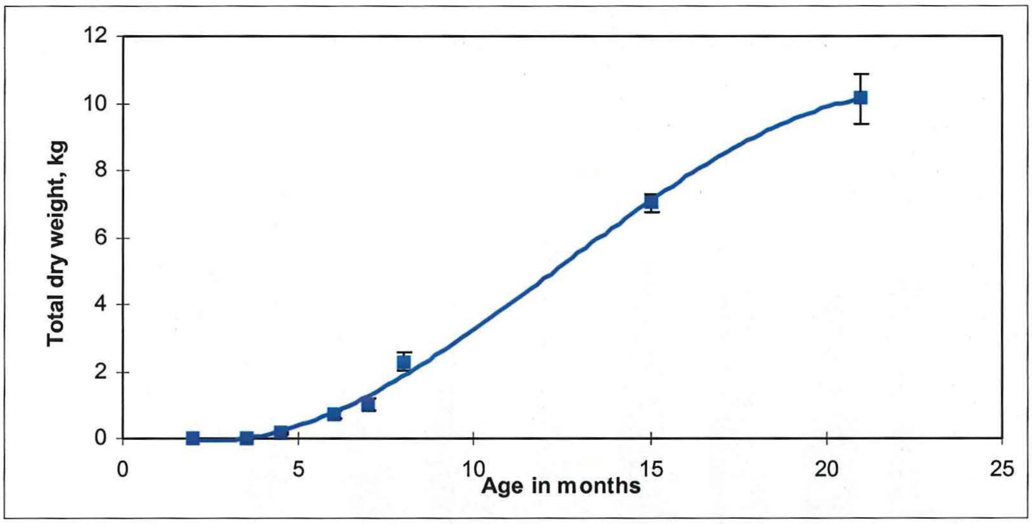
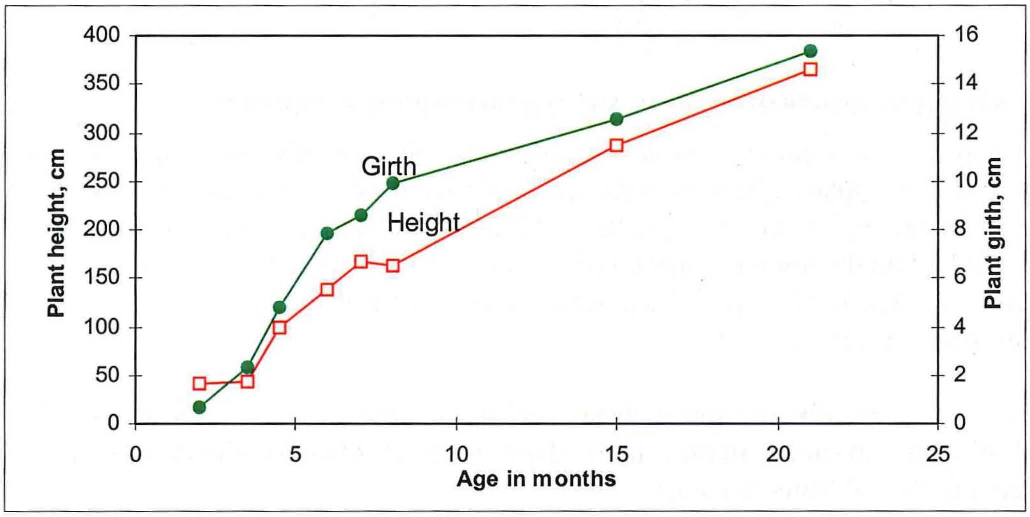


Figure 22 The increase in stem girth and plant height with age



Plant size as measured by height and girth (Fig 22) both changed rapidly, particularly in the first year, confirming the trends shown by dry matter changes of Fig 21.

Regression of tops dry weight and total dry weight for plants aged 3.5 to 21 months revealed useful relationships with height and girth, with respectively R^2 values of 0.748 and 0.75. The equations describing the relationships are:

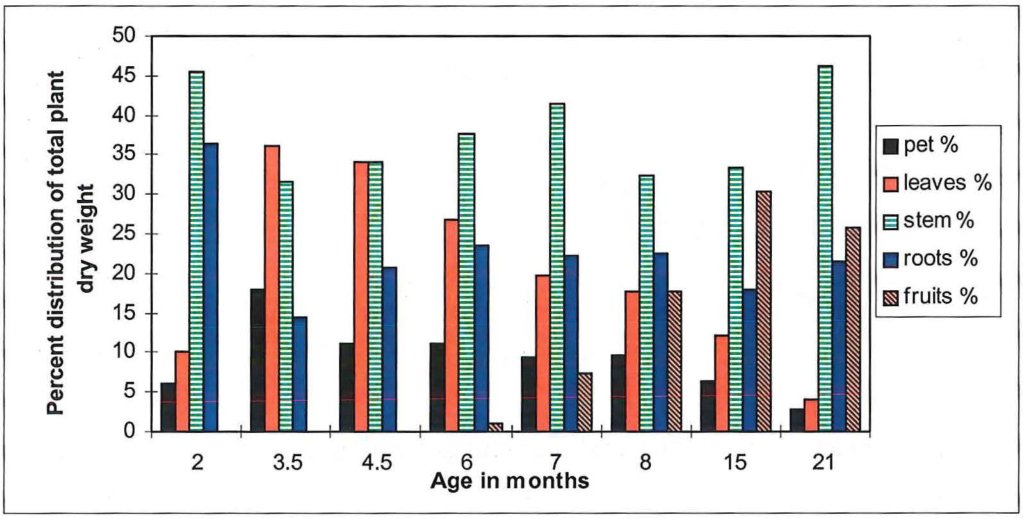
1. Tops DW(kgs) = 0.0356*Height(cm) - 0.423*girth(cm)
2. Total DW(kgs) = 0.0422*Height(cm) - 0.4877*girth(cm)

Such equations might be used in assessing tree productivity or harvest index (HI) calculations where HI = fruit kgs/total tree kgs with all weights on a dry weight basis. The plant biomass dry weight could be calculated by entering girth and height.

Leaves decreased from 35% at age 3.5 months to <5% of total plant dry weight at 21 months (Fig 23), whereas fruits increased from 0 to >30% over the same period.

Stems remained fairly constant at 30 to 46%, and roots 15 to 24% excluding the 2 month data. Petioles followed the declining pattern of leaves, and represented about half of the leaf biomass on average.

Figure 23. The percentage distribution of dry matter in plant organs with age.



12.3.2 NUTRIENT CONCENTRATIONS AND DISTRIBUTIONS IN ORGANS

Table 15 shows the range in nutrient concentrations with age of various plant organs. For N there is an apparent increase with age in N (%) for all organs, with leaves having by far the highest concentrations. For P there was little change across ages with leaves also having the highest concentrations. Potassium revealed very high root concentrations, followed by petioles and stems. Both Ca and Mg had highest concentrations in leaves.

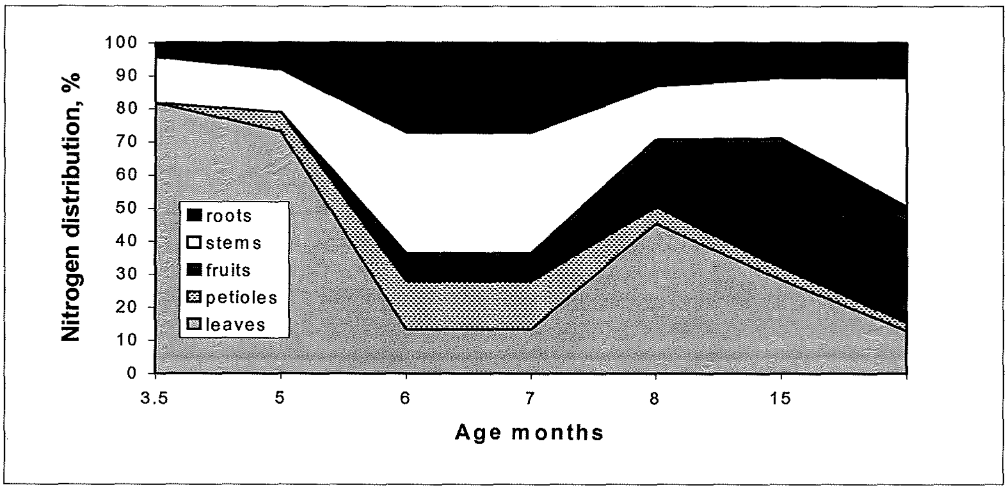
Papaya leaves generally had the highest nutrient concentrations but because of their limited biomass in older plants, their share of total plant nutrients was not as significant as that of fruits or stems.

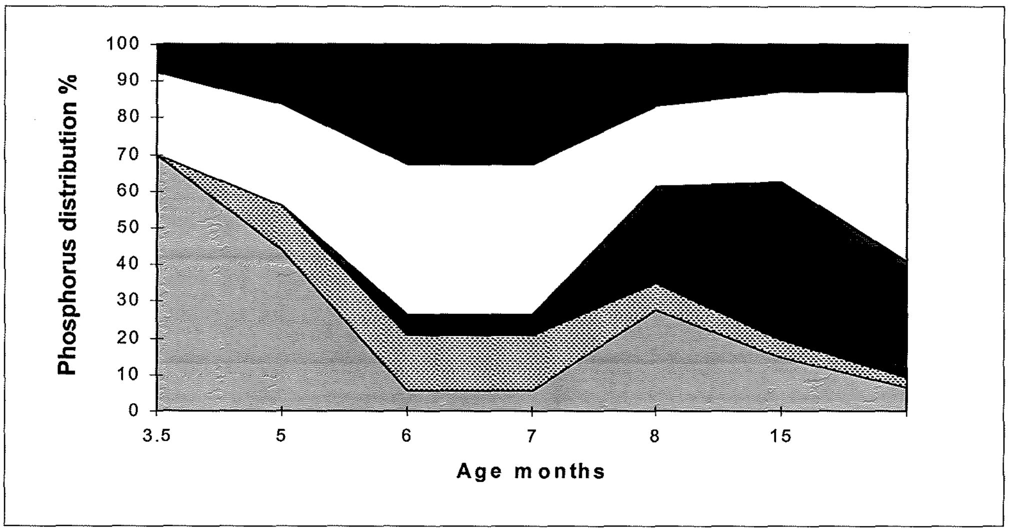
Using the results of Table 15 and Figs.21-23 the distribution of nutrients with age were calculated (Figs. 24 (a)..(e)). The pattern of leaf N distribution with age appeared to be bimodal, with highs at 3.5 months and 8 months. In mature plants, stems and fruits represented the largest storage/usage of N. In mature plants, stems and fruits were the largest storage/usage of P, K Ca and Mg, and given the large stem biomass this is not surprising. Roots were found to be important sources of K in plants of all ages, and the high demand for K by fruits of mature plants is indicated by Fig 24(c).

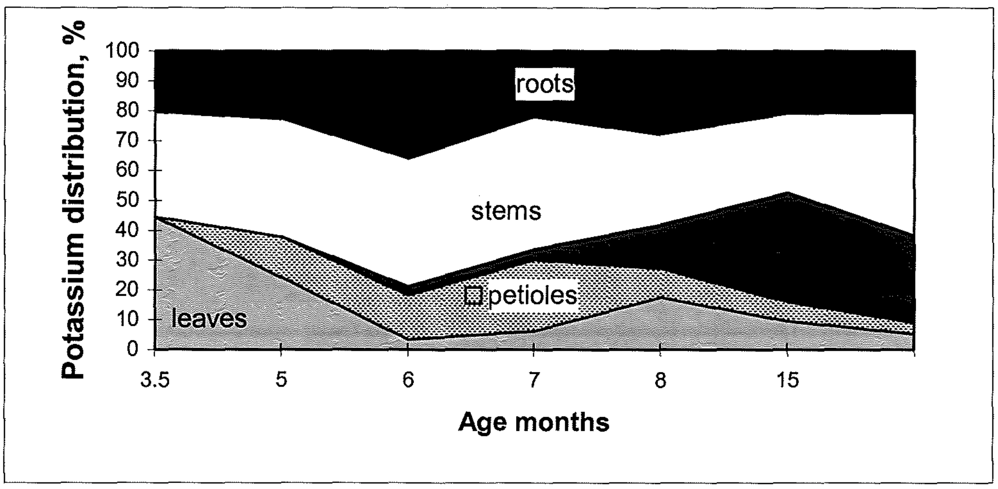
Table 17. Nutrient concentrations of plant organs used for nutrient content calculations

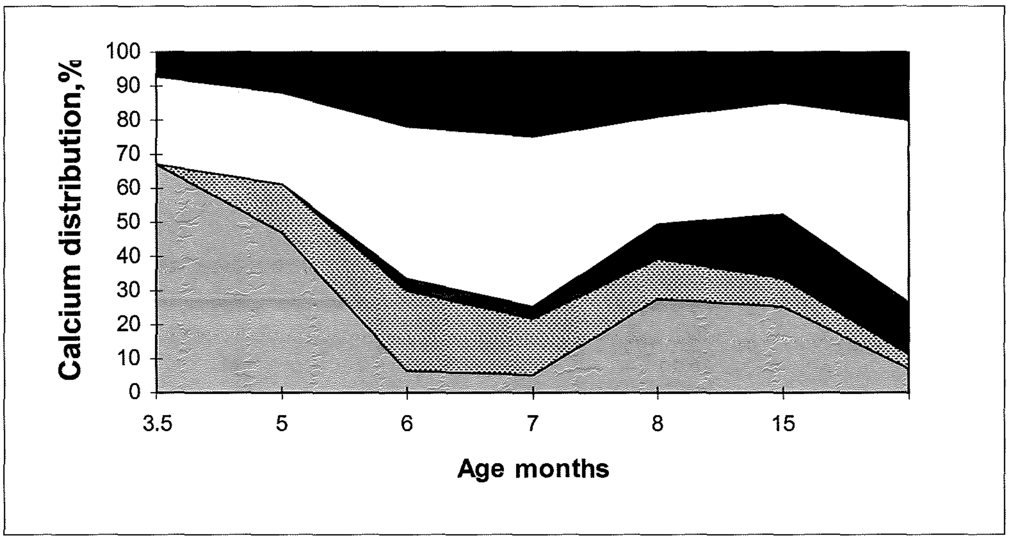
	Age in months						
N (%)	3.5	5	6	7	8	15	21
Leaves	3.5	3.76	2.8	4.39	3.99	4.44	4.53
Petioles		0.89	0.82	0.89	0.85	1.05	1.26
Fruits-gmf					1.8	1.97	1.86
Mid stems	1.1	0.68	0.63	0.77	0.76	0.86	1.06
Roots	0.69	0.68	0.73	0.62	0.9	1.1	
P(%)							
Leaves	0.35	0.49	0.42	0.63	0.43	0.32	0.44
Petioles		0.41	0.2	0.44	0.2	0.18	0.22
fruits-gmf					0.41	0.3	0.31
Mid stems	0.21	0.31	0.26	0.47	0.19	0.15	0.23
Roots	0.14	0.3	0.32	0.43	0.19	0.19	
K(%)							
Leaves	3.97	3.29	3.21	3.51	3.48	2.14	3.02
Petioles		5.75	3	3.34	3.56	2.71	3.37
fruits-gmf					2.96	2.68	2.53
Mid stems	5.85	5.44	3.37	3.23	2.69	1.74	1.84
Roots	6.65	5.07	4.41	4.9	4.28	3.1	
Ca(%)							
Leaves	1.65	1.27	1.11	1.54	1.49	1.94	1.38
Petioles		1.17	0.9	1.48	1.17	1.21	1.28
fruits-gmf					0.53	0.38	0.44
Mid stems	1.2	0.74	0.66	0.81	1.02	0.91	0.78
Roots	0.63	0.51	0.51	0.59	0.78	0.77	
Mg(%)							
Leaves	0.9	0.94	0.71	0.96	0.96	1.98	1
Petioles		0.88	0.5	0.86	0.57	0.91	0.85
fruits-gmf					0.38	0.33	0.37
Mid stems	0.87	0.72	0.56	0.62	0.61	1.12	0.64
Roots	0.42	0.38	0.43	0.36	0.66	1.18	

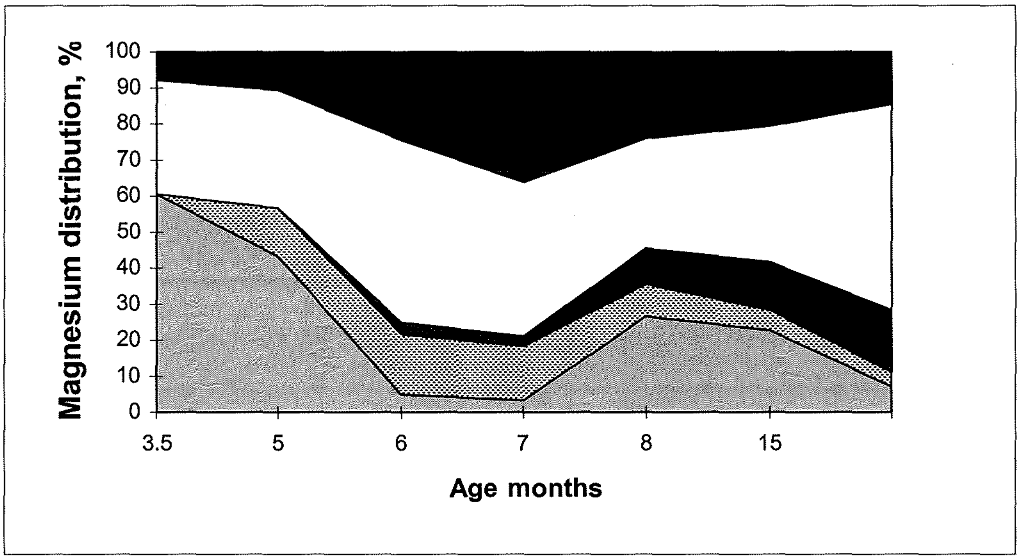
Figure 24 The percentage distribution of total plant nutrient content in organs with age for (a)N , (b) P, (c) K, (d) Ca and (e) Mg.









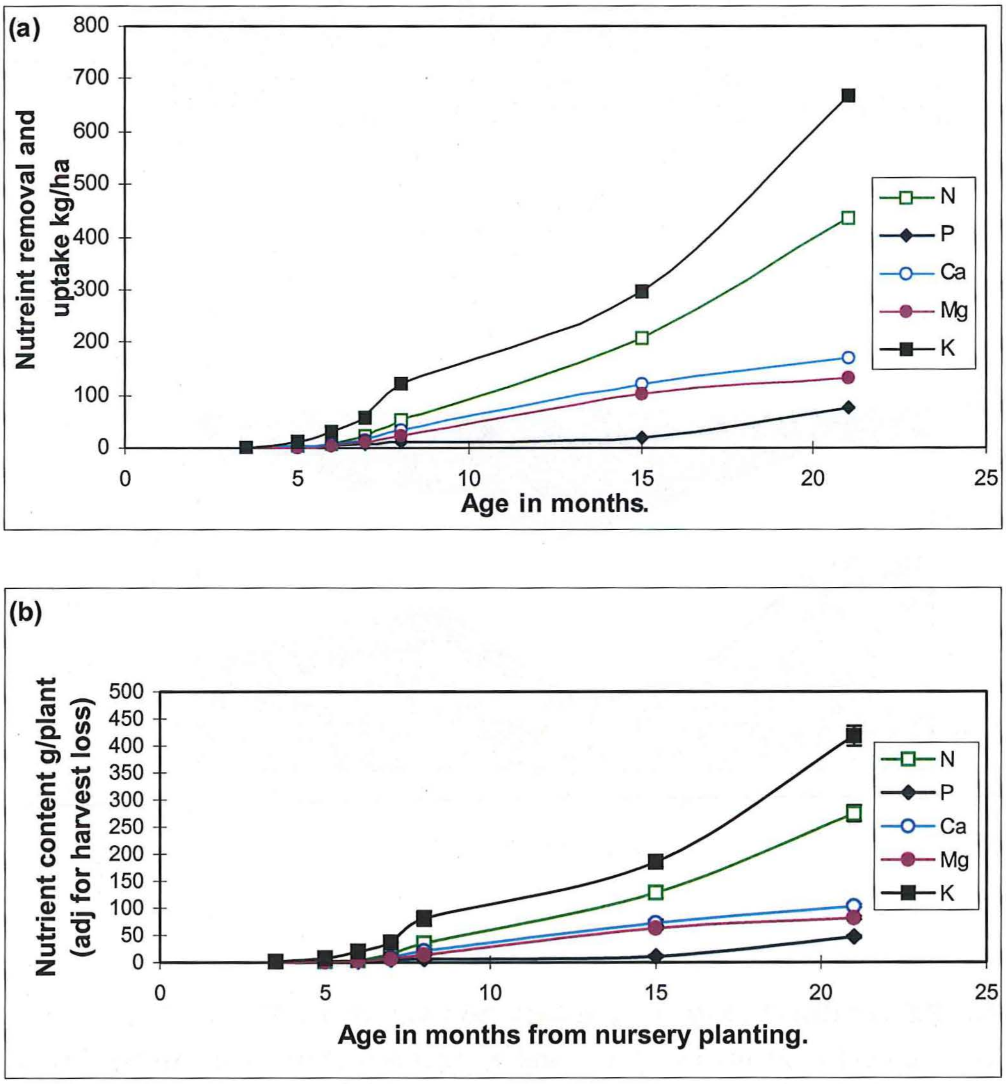


12.3.3 Nutrient contents in uptake and removal with age

Total plant nutrient contents as uptake and as removal (harvested losses) for each nutrient were calculated on a kg/ha basis and g/plant basis (Figs. 25(a) and (b)). For kg/ha basis 1666 plants per hectare were assumed for uptake and 1500 plants/ha for harvest removal, representing 10% male pollinator plants. Both N and K follow strong exponential increases with age, whereas Ca, Mg and P have somewhat flatter response curves. Potassium emerges as the most important nutrient on a whole plant basis, with its importance increasing with age rapidly after the fruiting phase commences. In contrast P is seen to be the least significant of the macronutrients. Standard error bars (Fig 25(b)) indicate reasonably small variations about mean values. Nutrient ratios describing total plant uptake and harvest requirements(i.e. the amount of each nutrient to be replaced that is lost through removal by harvesting) are of the order:

K: N: Ca: Mg: P: as9 : 6 : 2.2 : 2 : 1

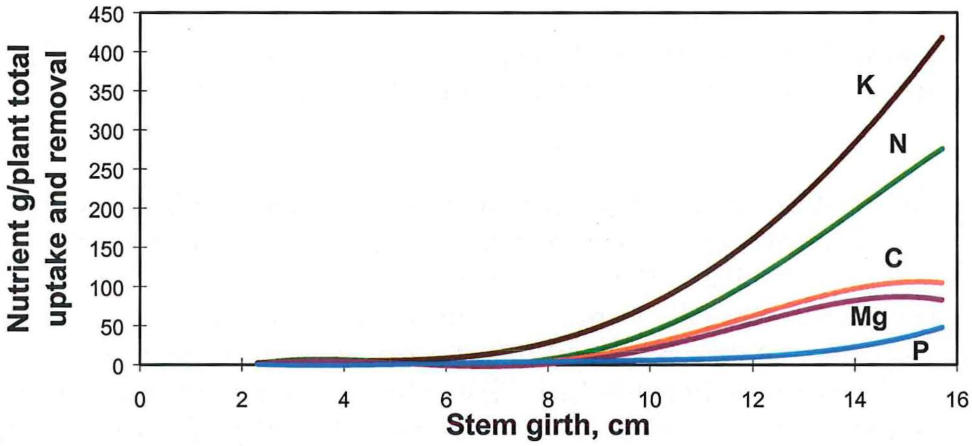
Figure 25. Nutrient removal and uptake (adjusted for harvest loss) for papaya plants with age for (a) kg/ha basis and (b) g/plant basis. S.E bars are shown for 5(b) for 8, 15 and 21 months data.



Very good relationships of nutrient content with tree size (stem girth) were obtained for N, K, Ca and Mg using non-linear regression models, which described logistic response curves as detailed below and in Figure 26.

$$\textbf{K g/plant} = 650.5/(1+ \exp.(-0.464(\textbf{girth}-14.44))\ \ R^{2=0.99}$$
$$\textbf{N g/plant} = 323.8/(1+ \exp.(-0.667(\textbf{girth}-13.109))R^{2=0.99}$$
$$\textbf{Ca g/plant} = 107.3/(1+ \exp.(-0.807(\textbf{girth}-11.58))\ \ R^{2=0.99}$$
$$\textbf{Mg g/plant} = 83.3/(1+ \exp.(-1.00(\textbf{girth}-11.39))\ R^{2=0.99}$$

Figure 26. Nutrient removal and uptake g/plant in relation to plant size as measured by stem girth.



12.4 DISCUSSION AND CONCLUSIONS

Reddy and Kohli(1989) reported results of papaya destructive sampling in India, showing very close trends in the distribution of dry matter as that of Figure 23 . However, total maximum dry weights at 16 months were 2.48 kg/tree which was well below that of the current study at about 7.1 kgs/tree. Factors relating to the differences will include cultivars, the high density of 3086 plants/ha in India, lower fruit yields at 18.35kgs/tree (cf. 78kg/tree), climate, soil and nutritional factors.

The importance of stems and fruits of papaya as storage organs for all the macronutrients is apparent from this study, as is the high requirements for K by papaya plants particularly in roots and fruits. The high rate of fruit production by papaya crops (135t/ha/year) means that subsequent removal of this harvested fruit draws large quantities of nutrients from the plant/soil system. Referring to Table 15, this removal at maturity, equates to 46% of total uptake and removal for K down to 23% for Ca, with other nutrients in between. There is no doubt thus that the nutrient requirements of papaya under tropical, irrigated management are high, and papaya growers in north Queensland believe this also; survey results have shown that mean application rates are 692 kg/ha N, 414 kg/ha P, and 940 kg/ha K per 2 year cycle (Richards *et al* 1995). The sustainability however of such high average industry application rates does need to be considered, in the light of results from this study and the papaya nutrition trial which indicated that rates of applied N above 300 kg/ha and applied K above 574 kg/ha does not increase yields. For bananas, in NQ no response above 100 kg/ha/yr of applied N was obtained (Armour and Daniells 2002)

Experimentation with several different tree crops overseas shows that large fertiliser applications in excess of that removed by crops are wasteful, as they result in little or no additional yield (Weinbaum *et al.* 1992). These authors concluded that applications of N in soils adequately supplied with N results in low nitrogen use efficiency and is potentially damaging to the environment.

How much fertiliser does papaya require for growth and yield?

This issue needs to be addressed by considering how much of each nutrient is required for fruit production, how much for plant uptake and growth and what are the soil reserves and rate of release from nutrient pools. Tagliavini *et al.* (1996) proposed a simple formula to relate these factors whereby :

Recommended fertiliser application rate kg/ha = (amount of nutrient required from 1 stage to next) -{(soil nutrient conc mg/kg)*(soil volume m^3)*(soil bulk density kg/ $m^{3)*10E-6)}$

Geypens and Vandenriessche (1996) summarised the major fertiliser advisory N systems as being based on either soil mineral N contents, plant or sap analysis, or based on simulation models. They concluded that systems based on N mineral contents and dynamics generally work well. Plant and sap analysis are useful tools to determine the uptake of N and to determine frequency of application, but not the amount to apply. Simulation models have been used for research purposes and have no practical commercial significance to date, but sub-models for leaching and mineralisation may be readily integrated into recommendations such as N index or N balance sheet methods.

Table 18. Nutrient requirements to satisfy harvest removal and plant uptake in papaya at various ages.

	3.5 mths kg/ha	5 mths kg/ha	6 mths kg/ha	7 mths kg/ha	8 mths kg/ha	15 mths kg/ha	21 mths kg/ha
N							
Uptake	0.86	4.21	6.65	23.5	43.3	124.8	248
Removal	0	0	0	0	10.8	82.2	187
Total	0.86	4.21	6.65	23.5	54.1	207	435
P							
Uptake	0.1	0.91	2.42	7.52	7	10.4	44.6
Removal	0	0	0	0	2.5	8	30.4
Total	0.1	0.91	2.42	7.52	9.5	18.4	75
K							
Uptake	1.8	11.1	30.2	55.2	103.5	187	362
Removal	0	0	0	0	18	108	306
Total	1.8	11.1	30.2	55.2	121.5	296	668
Ca							
Uptake	0.5	2.2	5.7	14.4	29.8	100	130
Removal	0	0	0	0	3.2	20	39
Total	0.5	2.2	5.7	14.4	33	120	169
Mg							
Uptake	0.3	1.8	4.3	9.7	18.8	87.3	99
Removal	0	0	0	0	2.2	15.6	34
Total	0.3	1.8	4.3	9.7	21	103	133

Given the extremely good relationships obtained between stem girth and total nutrient content per plant (Fig 26), Table 18 data might be better applied on a tree size basis, as age and growth relationships will be highly dependent upon environmental factors. Thus by measuring stem girth and having yield data, the results of Table 17 could be applied and amended for use in the equations as proposed by Tagliavini *et al.* (1996) to arrive at basal fertiliser applications for commercial usage, more in tune with plant requirements and soil supply rates, as indicated in Figure 26. Foliar and soil analysis could be used to check that nutrients are indeed being taken up sufficiently (as indicated by adequacy levels) and changes made to the basal programme. In this way, papaya growing anywhere in Queensland could have reasonable nutrient application models developed based on plant age/girth, soil nutrient status, yield function, plant density and the results of Table 18.

CHAPTER 13: RESPONSE OF YOUNG PAPAYA TO NITROGEN APPLICATIONS

13.1 INTRODUCTION

The nutrient management of immature, fast growing plants is often overlooked with most efforts directed towards mature plant needs. In Chapter 5, several relationships of plant age and size, with nutrient uptake and losses were established, and pointed towards a low level of required nutrient input pre-flowering. Chapter 6 reports on a field study to examine papaya responses to 3 levels of applied N from seedling stage to early flowering. The rates of N were modeled on predicted needs as established from Chapter 5 data.

13.2 METHODS AND MATERIALS

Papaya plants of hybrid 1B were planted in late October 1996 at South Johnstone Research Station at equivalent density of 1666 plants per hectare. Ten plants in three groups were selected to monitor stem girth (15cm above ground), crown height and numbers of flowers and fruit per tree at fortnightly intervals, commencing 24/01/97. The tree groups were allocated to fertiliser N treatments of zero, medium and high N fortnightly applications which commenced 24/01/97, by which time many plants had already commenced flowering. Prior to this all plants had received 50g/plant of NPK 15/15/15 at planting. The medium treatment applied 15g/tree /fortnight of ammonium nitrate and the high treatment 30g/tree/fortnight.

Petiole sap samples were taken at regular intervals using 4 petioles per treatment, collected from the most mature petiole in non-flowering plants, or the petiole subtending the most recently opened petiole, in flowering plants. Soil nitrate was also measured regularly using 15 cm depth samples, bulked over each treatment. Results in soil solution and sap extracts were determined using an RQFlex reflectometer as outlined in Chapter 4.

Data from plants in the papaya Nutrition Trial (Chapter 3) were also studied in the immature phase, as part of this report

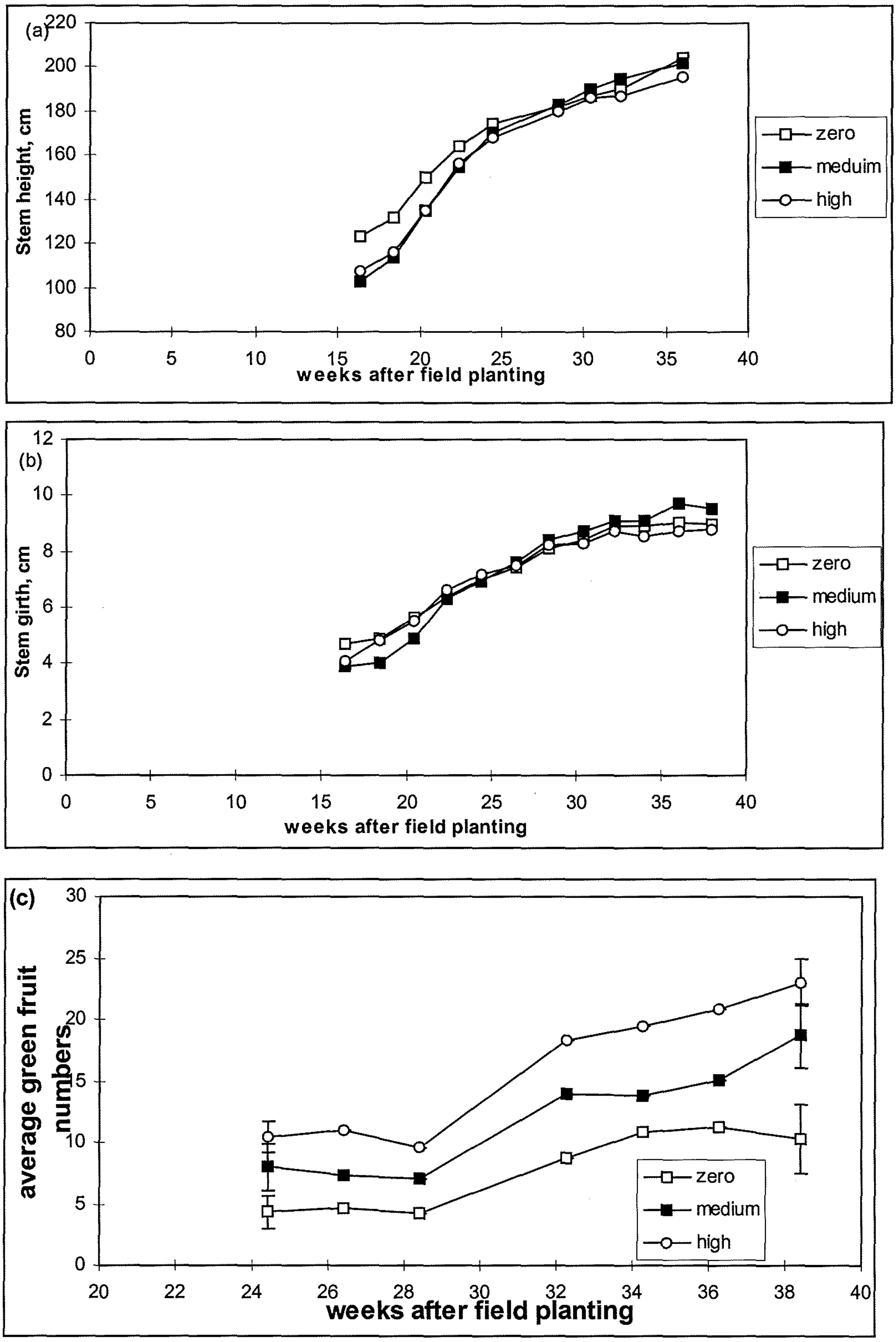
13.3 RESULTS

13.3.1 GROWTH AND FRUITING RESPONSES

Papaya plants grew rapidly in all three treatments as indicated by Figs. 27(a) and (b). The zero treatment plants were initially significantly larger than both other treatments, but at the conclusion by week 36 there were no significant differences in either height or girth.

Fruit numbers per tree (mean) recording commenced 23/03/97 and showed consistently higher numbers per plant with the high rate (Figure 27(c)). At the conclusion, medium and high rates were equal, and both were significantly higher than the zero treatment.

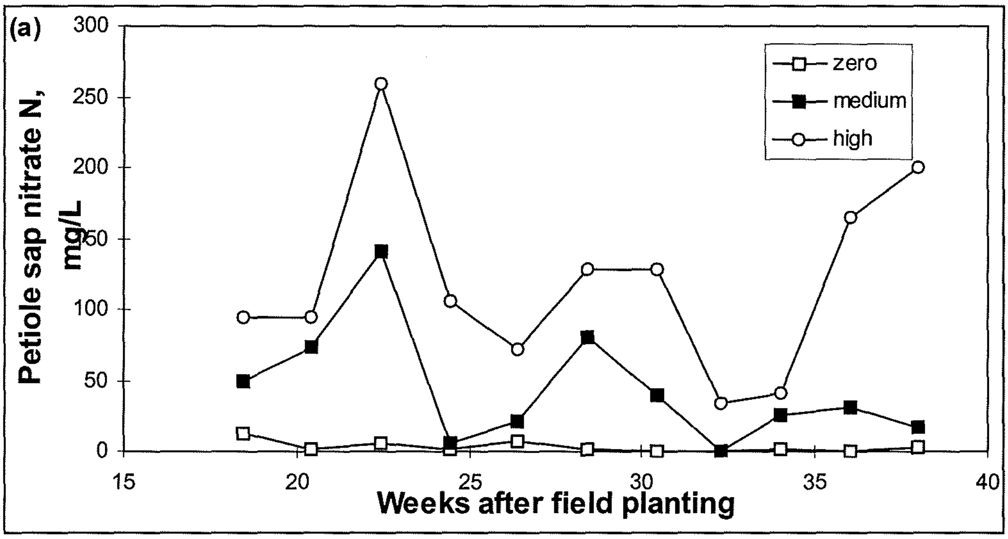
Figure 27. Changes in mean crown height (a) and stem girth (b) with weeks after field planting, at three rates of applied N (zero, medium, high).

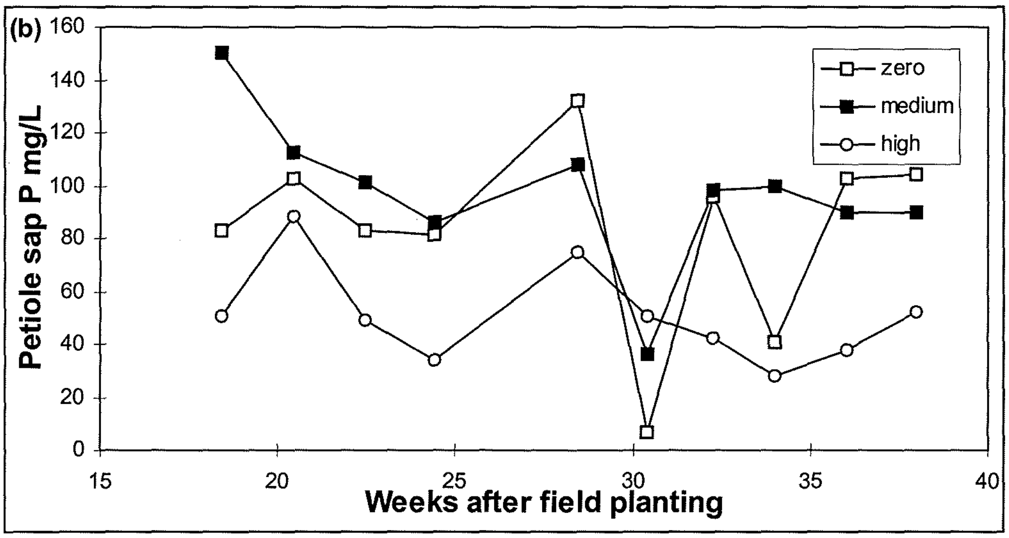


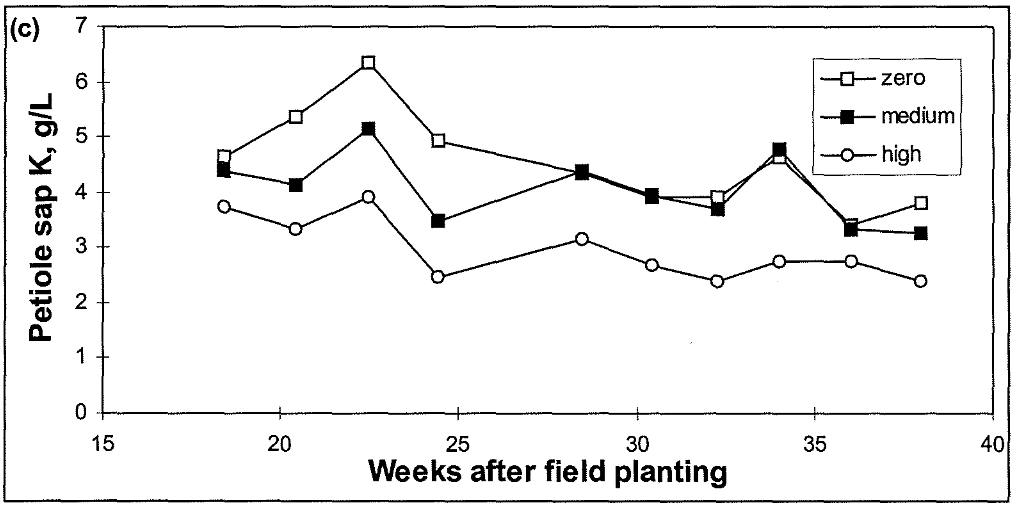
13.3.2 PETIOLE SAP CONCENTRATIONS AND SOIL NITRATE LEVELS.

Petiole sap (RQFlex) nitrate N was always highest in the high treatment plants (mean 120 mg/L) and least in the zero treatment plants (mean 3 mg/L) as shown in Fig. 28(a). High treatment values always exceeded the tentative critical level of 35 mg/L as established in Chapter 3.3 for mature plants, and zero treatments were always much less than this concentration. Medium treatment nitrate N concentrations fluctuated either side of this limit with a mean of 44 mg/L. Petiole sap P concentrations were generally least in the high treatment plots with zero and medium similar (Figure 28(b)). Petiole sap K followed a similar trend as did petiole sap P, and petiole sap indicated adequate concentrations of both P and K.

Figure 28. Petiole sap nitrate N mg/L (a), sap P mg/ L (b), and sap K g/ L (c), at different times after planting.

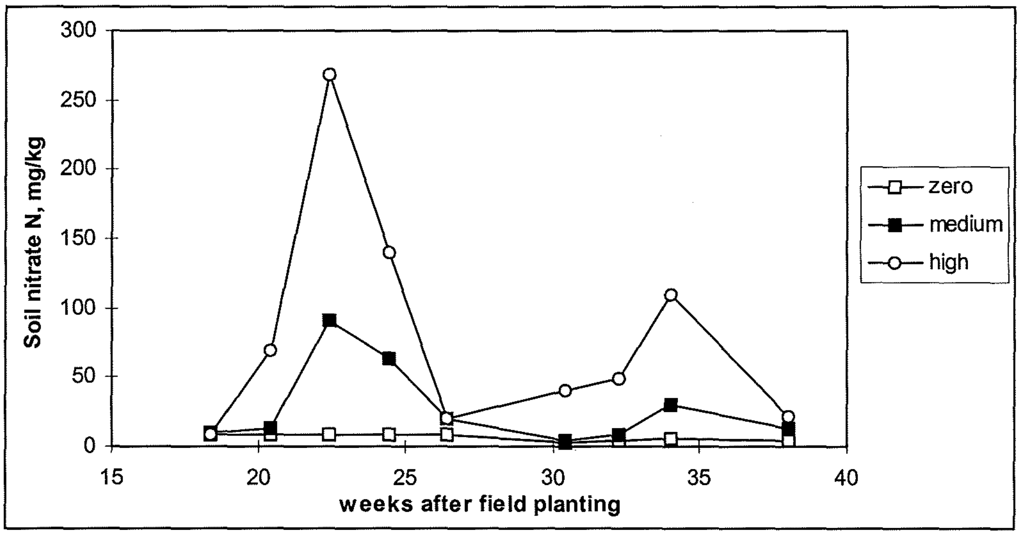






Soil nitrate N levels were often high in the high treatment plots and always very low (mean 6 mg/kg) in the zero plots (Fig. 29). Medium treatment plots were generally more acceptable with a mean of 28 mg/kg and high plots had a mean of 80 mg/kg which is unnecessarily high compared to the tentative mean of 30 mg/kg as established in Chapter 3.2.

Figure 29. Soil nitrate N mg/kg soil, with weeks after planting



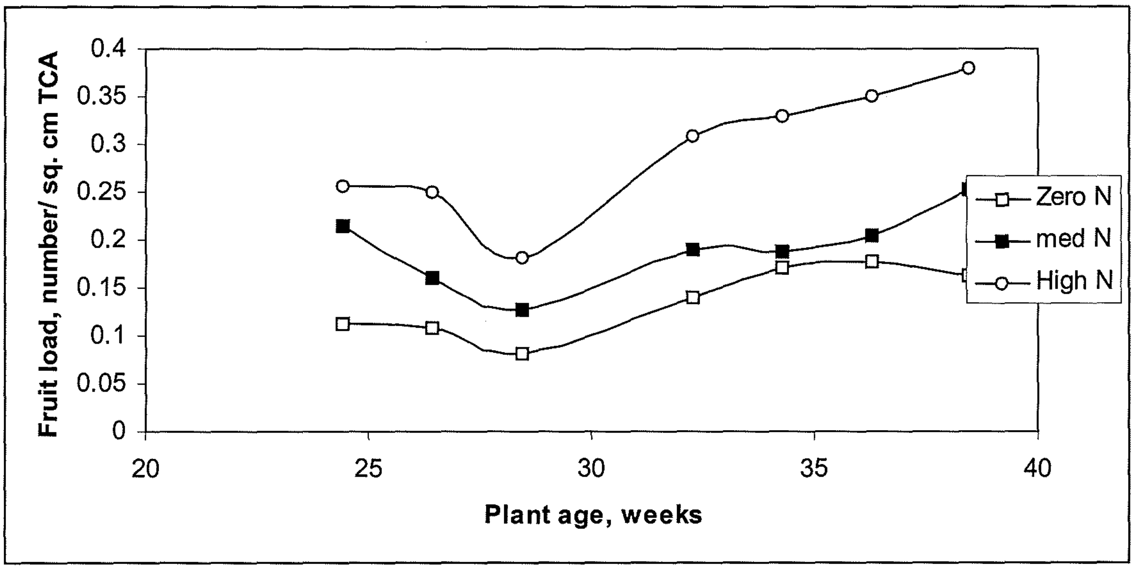
13.3.3 Responses to cumulative N applied

Cumulative N applied per tree for each treatment over 8 months and plotted with stem girth indicates that the zero treatment was well able to use existing available N supply to attain growth similar to the other treatments (Fig 30 (a)). Fertiliser wastage associated with particularly high rates equivalent to 200 kg/ha of N for an 8 month period (high N) is evident, however plants that did not receive N were larger at the start of this trial (Figs26 a, b) and were not significantly larger at the end of the trial. In contrast, medium rates were equivalent to 100 kg/ha and zero rates 10 kg/ha of N. Figure 30 (b) which covers a 10 month period using Nutrition Trial data, suggests that for immature plants up to less than 11 cm stem girth, about 40 g N /plant is required which is approximately 4gN/tree/month. This is very low but does confirm the results achieved for zero rate in Fig 30(a), in which only 10g N were applied over 8 months. However fruit production was reduced at the zero rates thus the zero N rate is likely to be too low. Medium N rates applied 60 g N per plant over 8 months, or 7.5 g/plant per month on average. It seems that to allow for a margin for fruiting and flowering, a rate between zero and medium rates should be selected for this soil type.

An indication of fruiting efficiency was sought using number of fruit per tree as an indicator of fruit load, revealing that fruit load increased with increasing N application (Figure 30).

Final fruit loads were 0.16, 0.25 and 0.37 fruit/cm^2 TCA for zero, medium and high rates, and given that both high and medium fruit numbers per tree were not significantly different, the medium rate seems adequate in terms of N supply. The cumulative amounts of N applied upto 25 weeks were 6g/plant zero, 63 g/plant medium, and 126 g/plant high N.

Figure 30. Fruit load per plant (number/ Trunk cross-sectional area sq.cm) in relation to cumulative N applied.



An attempt at a nitrogen balance sheet was made, recognising that soil total N% (not measured) would be an important input into this process. However it was assumed that gross comparisons could be made by relating results to the zero N treatment which relied upon the mineralisation of total N to supply N over the period. The results are presented as Table19.

The results of this balance sheet point to a high degree of N wastage/loss at high rates of N applied, over the early fruiting stage, with more acceptable levels at the medium rate. Due to the higher fruiting load (not significant) in high and medium rate treatments, the uptake of N may be substantially higher than that calculated. The use of between 40 and 70 g/plant applied N over 8 months seems to be a reasonable baseline application level for this soil type and climate. This is about 8g N /tree/ month.

Table 19. Approximate N balance sheet for immature papaya plants.

Item	Zero rate	Medium rate	High rate
Soil Nitrate N g per plant at start *	9	10	9
g N added/plant	6	63	126
Total N supply, g/plant	15	73	135
Calculated uptake g/plant**	13	27	17
Supply less uptake g/plant	2	46	118
soil nitrate N g/plant at end*	4	11	17
N unaccounted for, g/plant	-2	35	101

* assuming soil depth 20cm, bulk density 1260kg/m^3 , volume soil /plant 0.63 m^3.
** assuming uptake rate based upon mean girth as established in Chapter 3.4.

13.4 Discussion and conclusion

The wastage associated with high fertiliser application rates in the immature growth phase of papaya was evident in this study. Zero application rates, which relied upon soil mineralisation of N produced similar size trees, but suffered from reduced fruit numbers and reduced fruit load, compared with both medium and high N application rates. The nitrogen balance sheet suggested a large wastage/loss at high rates, with acceptable surplus at medium rates, although this could be lowered further.

By using fortnightly sap and soil quick test methods (ie RQFlex reflectometer) it should be possible and practicable for growers to schedule N applications based upon growth measurements and tentative threshold levels of about 30 mg/Kg soil nitrate N and 35 mg/L petiole sap nitrate N, working from a basal programme of applying 8g N per plant per month up to age of about 8 months for a total of 64 g/plant. This is equivalent to 106 kg/ha N over 8 months (311 kg/ha ammonium nitrate).

CHAPTER 14: SUSTAINABLE NUTRIENT MANAGEMENT PRACTICES FOR PAPAYA PRODUCTION

How then does one put it all together into a management system for more sustainable papaya production?

14.1 START WITH A PREPLANT SOIL ANALYSIS

In particular this will indicate the amount of lime required to adjust soil pH to the required level. Without a soil analysis you are just guessing. Normally soil tests are just done on samples from the top 15cm. Additional measurement of pH from 15-40cm? below the soil surface will be useful to determine if acidity is a problem towards the bottom of the root zone. Soil analysis will also indicate phosphorus requirement and likely nitrogen requirement. Papaya have a small P requirement so current rates are luxurious.

14.2 PREPLANT INCORPORATION OF BASAL FERTILISERS

Moist surface applied lime is only effective to a depth of about 10cm. Incorporation will greatly increase the effectiveness of liming by moving some of the lime deeper in the soil as well as being less subject to erosive losses. Preplant incorporation of P fertilisers also renders it less subject to erosive loss and potential adverse environmental impacts offsite. It should be possible to supply most of the papaya crop's lime and P requirements preplant.

14.3 REDUCE NITROGEN AND POTASSIUM APPLICATION RATES

Depending on the soil analysis and subsequent plant/soil analyses aim to apply about 340kg/N/ha/2 years and 650kg K/ha/2 years. In our trial the fertilisers were broadcast. It should be possible to reduce the fertiliser rates further (perhaps 30%) by the use of fertigation. Decreasing nitrogen fertiliser application will also reduce the rate of soil acidification as we found in our trial so arresting the decline in cation exchange capacity and reducing the lime requirement.

14.4 MATCH FERTILISER APPLICATION RATES TO PLANT GROWTH

Our results (Figure 25) show the nutrient uptake pattern at different periods after planting. Absolute plant requirement per fertiliser application were greater for larger plants during warmer conditions. Firstly set a target application for the crop and then aim to increase fertiliser applications in synchrony with plant growth. Use sap nutrient monitoring to finetune applications.

14.5 Monitor nutrient levels in petioles by sap and plant analysis

Fortnightly monitoring of sap petiole N and K levels will check the effectiveness of your fertiliser management program. Applications can be increased/decreased as required. These can be crosschecked with 6 monthly standard leaf analyses.

14.6 Apply nitrogen and potassium frequently

In our trial N and K fertilisers were applied broadcast every month. Applying fertilisers in small quantities frequently greatly enhances fertiliser use efficiency and reduces losses. Fertigation is ideal in most cases for this purpose – aim to apply fertiliser at least every 1-2 weeks.

14.7 Maximise crop uptake

Nutrients taken up by the crop are protected against loss. Ensure the crop is well managed so that other factors such as pest/disease/irrigation do not limit growth and fertiliser uptake.

14.8 Ground cover management

Ground covers are important for protecting the soil surface from the loss of soil and fertilisers by erosion. The interrow trafficway is usually grassed and slashed as required. There is considerable variation in management of the mounded row due to interactions with phytopthora root rot management. Additional studies are needed on this subject to identify other living or dead mulches that do not compete too vigorously with the crop and that do not exacerbate phytopthora problems.

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17: APPENDIX

Project Publicity

Richards, N.K. and Dostie, B. 1996 Nutrition and irrigation. Papaya Information Booklet . SJRS Field Day, 3 August 1996 pp 2-3.

Ross, P., O'Hare, P., Macleod, N., Kernot, I., Evans, D., Grice, K., Vawdrey, L., Richards, N.K., Blair, A., Astridge, D. and Chay-Prove, P. 2000Papaw Information Kit . Agrilink Series QAL9910