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SOIL MOISTURE AND PROFILE NITROGEN OF A WATERMELON CROP

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SOIL MOISTURE

and

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WATERMELON CROP

Changes in soil moisture status
and profile nitrate distribution
under a commercial crop of
watermelon (*Citrullus lanatus*) grown
at Katherine, Northern Territory.

August 1991

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SUSTAINABLE AGRICULTURE

THE DEPARTMENT OF PRIMARY INDUSTRY AND FISHERIES IS COMMITTED TO THE PRINCIPLES AND PRACTICES OF SUSTAINABLE AGRICULTURE

Definition:

Sustainable agriculture is the use of practices and systems which maintain or enhance:

- the economic viability of agricultural production;
- the natural resource base; and
- other ecosystems which are influenced by agricultural activities.

Principles:

1. Agricultural productivity is sustained or enhanced over the long term.
2. Adverse impacts on the natural resource base of agricultural and associated ecosystems are ameliorated, minimised or avoided.
3. Harmful residues resulting from the use of chemicals for agriculture are minimised.
4. The nett social benefit (in both dollar and non-dollar terms) derived from agriculture is maximised.
5. Agricultural systems are sufficiently flexible to manage risks associated with the vagaries of climate and markets.

CONTENTS

ABSTRACT:

Soil moisture and profile nitrate distribution were assessed at ten intervals during the growth of a commercial watermelon crop. It was found that crop water use changed during the life of the crop. Water use reached a peak around 65 days after planting which coincided with mid-fruit filling stage. Crop water use was also shown to be sensitive to changes in soil moisture content. Serious reductions in transpiration rate were not associated with visible signs of plant stress such as wilting.

Nitrate concentration and distribution showed considerable change during the life of the crop. The largest amount of nitrate was detected in the profile at 42 days after planting and amounted to 108 kg Nitrate/ha. Calculations based on these results suggested that the rate of plant nitrogen uptake also varied with crop development. It was estimated that a peak nitrogen extraction rate of 3.8 kg N/ha/day occurred around 46 days after planting and coincided with fruit set and rapid expansion in ground cover.

Nitrate extraction continued up until final sampling with an increasing proportion of extraction taking place at depth as the crop aged. Only small quantities of nitrate remained in the profile at final sampling. It was shown that a highly productive commercial crop could be grown without significant leaching.

INTRODUCTION:

Watermelon (*Citrullus lanatus*) is grown commercially in the Northern Territory during the months March to November with most production occurring between May and November. Total production for the 1990 season was 1458 tonnes, 26 percent of which was grown in the Katherine region (Kraus 1991). Average yield for the 1991 season was 21.7 tonnes per hectare.

No rainfall occurs during the production season and hence the crop is grown entirely on irrigation. Although this makes irrigation a major production cost it also creates the opportunity to manage irrigation application precisely in accordance with crop water needs. Whilst most growers recognised that different crop growth stages require different irrigation applications, there had been no quantification of these responses. The high infiltration rates and low water holding capacities associated with soils used for production in the area, in conjunction with often large inputs of fertiliser and irrigation suggested that leaching could be a significant problem. Nitrate leaching in wet season cropping systems was studied extensively in the 1960's (Wetselaar and Norman 1960; Norman 1966; Norman and Begg 1973). However no data existed to indicate the significance of leaching as a problem under irrigated horticulture. Similarly, no base line information existed to describe nitrate distribution and uptake under current commercial management practices.

The present study was undertaken to fulfil these requirements and to provide some directions for future research.

MATERIALS AND METHODS:

General:
The experiment was located on a commercial property 17km south east of Katherine, Northern Territory (14°31'S., 132°27'E 108m altitude) during the 1990 dry season. The soil type was a Venn Class (formerly Blain) (Gn 2.11) (paleustalf) which has a loamy sand surface (Lucas, Day and Wood 1985; Northcote 1979; Soil Survey Staff 1975). Prior to 1990, the areas had been cleared of native vegetation in February 1989 and lay fallow until the experiment commenced. Hence it was a virgin area fallowed for nine months. The predominant native vegetation consisted of open forest *Eucalyptus tetradonata* with some *E. miniata* and *E. foelscheana* and an under storey of *Sorghum intrans* (Aldrick and Robinson 1972).

Six rain gauges were located, each 3 metres apart in a line parallel to the sprinkler line. These gauges were located 1.5 metres out from the sprinkler line and spaced so as to cover the interval between two sprinklers. Rain gauges were partially buried at each site such that they: could be easily read and emptied; would remain in exactly the same position throughout the experiment and; would intercept the actual amount of water applied at the soil/canopy surface. As the experiment progressed the gauges were raised approximately 200mm vertically so as to prevent the plant canopy interfering with measurements.

Cultural Details:
The experiment was located within a commercial planting of 0.98ha. Prior to planting, the site was disced and rotary hoed. Base fertiliser of the following composition was applied prior to cultivation:

Element	Form	Rate of element (kg/ha)
N	Ammonium sulphate	31
P	Double superphosphate	124
K	Potassium chloride	76
S		72
Cu		3.2
Zn		3.2
Mo		0.1

Watermelon (*Citrullus lanatus*) c.v. Allsweet was planted on the 13 July 1990 at a spacing of 1.5m by 1.6m. The first soil samples were collected on the 1 August 1990 when plants were at the three to four leaf stage. Forty millimetres of irrigation had been applied to the crop prior to the first sample being taken.

Side dressings of 41.1 kg N/ha and 35.2 kg N/ha as urea were applied on the 12th and 26th of August respectively. A further side dressing of 8.3 kg N/ha as potassium nitrate was applied on the 14th of September.

The crop was kept free from pest and disease. Harvesting commenced on the 1st October and continued until the 29th of October. The area was harvested as a commercial crop with only saleable fruit removed. Yields were recorded for each week of harvesting.

Sampling Procedure;
Soil samples were collected to a depth of 2 metres using a 100mm diameter hand auger. The top metre was collected in 200mm intervals. The intervals 1000 to 1300mm and 1500 to 1800mm were discarded and the intervals 1300 to 1500mm and 1800 to 2000mm retained. In addition, a sample was collected at the surface to a depth of approximately 10mm. This gave a total of 8 samples per core. Cores were taken within a 500mm radius of the respective rain gauge. The position within this radius at which the core was collected was determined randomly at each sampling date.

Initially, cores were collected at each rain gauge. This was latter modified so that three cores were collected (at gauges 1, 3 and 5). Samples were collected into sealable plastic bags and immediately placed on ice. Samples were taken at intervals of between five and twenty days throughout the life of the crop. This gave a total of 10 sampling dates. All samples were collected between 4.30pm and 7.00pm of the day in which irrigation was due to be applied. Samples were transported to the laboratory on ice. Here subsamples were taken for gravimetric moisture and nitrate determination.

Gravimetric Moisture;
Subsamples were taken from each bag, and immediately weighed. These were then dried for not less than 48 hours at 105°C and reweighed. Care was taken to ensure dried samples did not absorb moisture from the air prior to reweighing.

Nitrate Determination;
A further subsample was taken from each bag, added to a 10ml plastic centrifuge tube and the tube immediately sealed. The weight of this subsample was determined. Four millilitres of distilled water was added to each tube and the samples shaken for one hour. Samples were then centrifuged for twenty minutes at 2500 revolutions per minute in a bench top centrifuge. Nitrate concentration of the resulting supernatant was determined using Merckoquant test strips and a Nitrachek reflectometer.

The test strips were immersed in the supernatant for five seconds, removed and shaken to remove excess moisture, allowed to develop for sixty seconds and then inserted into the meter for nitrate determination. Standard solutions of known nitrate concentration were periodically tested to ensure correct functioning of the meter and strips. Care was taken to ensure the samples had been adequately centrifuged (clean supernatant) and that the soil was not disturbed when immersed the test strip. Nitrate determinations were carried out in an air conditioned laboratory at 22°C.

All samples were collected and processed within twenty four hours and mostly within six hours.

Climatic Information;
Precipitation was recorded and rain guages emptied after each irrigation. The duration of irrigation was also recorded. Irrigation commenced between 6.00pm and 8.00pm in all instances. Hence all samples were taken no more than three hours before irrigation was applied.

Relative humidity, daily maximum and minimum screen temperatures, incident short-wave radiation, and Class A pan evaporation were recorded at the Katherine Research Station (14^0 28' S., 132^0 18' E., 108 m altitude) for the period during which the experiment was conducted. These are presented in Figure 1. Pan evaporation data was also obtained from the CSIRO Manbulloo Site (14^0 47' S., 131^0 57' E., 120 m altitude) 63 km from experimental site and from the Douglas Daly Research Farm (13^0 50' S., 131^0 13' E., 80 m altitude) 152 km from the experimental site. Accumulated pan evaporation figures for the three sites are presented in Table 1.

Table 1. Comparison of evaporation figures from three sites for the period of the experiment.

Interval	No. of days	K.R.S. (actual)		DDRF (calculated)		CSIRO Manbulloo (actual)	
		Total evap. over period	Av. daily evap.	Total evap. over period	Av. daily evap.	Total evap. over period	Av. daily evap.
14.07.90 → 02.08.90	20	127.2	6.4	118.3	5.9	Not available	
03.08.90 → 11.08.90	9	52.0	5.8	59.7	6.6	Not available	
12.08.90 → 16.08.90	5	35.0	7.0	35.9	7.2	Not available	
17.08.90 → 24.08.90	8	59.9	7.5	58.9	7.4	Not available	
25.08.90 → 01.09.90	8	57.8	7.2	59.6	7.5	62.6	7.8
02.09.90 → 11.09.90	10	89.9	9.0	82.5	8.3	104.9	10.5
12.09.90 → 25.09.90	14	129.5	9.3	121.0	8.6	145.3	10.4
26.09.90 → 05.10.90	10	104.9	10.5	90.0	9.0	107.7	10.8
06.10.90 → 17.10.90	12	124.8	10.4	116.9	9.7	118.3	9.9
18.10.90 → 06.10.90	20	209.4	10.5	170.9	8.5	219.5	11.0

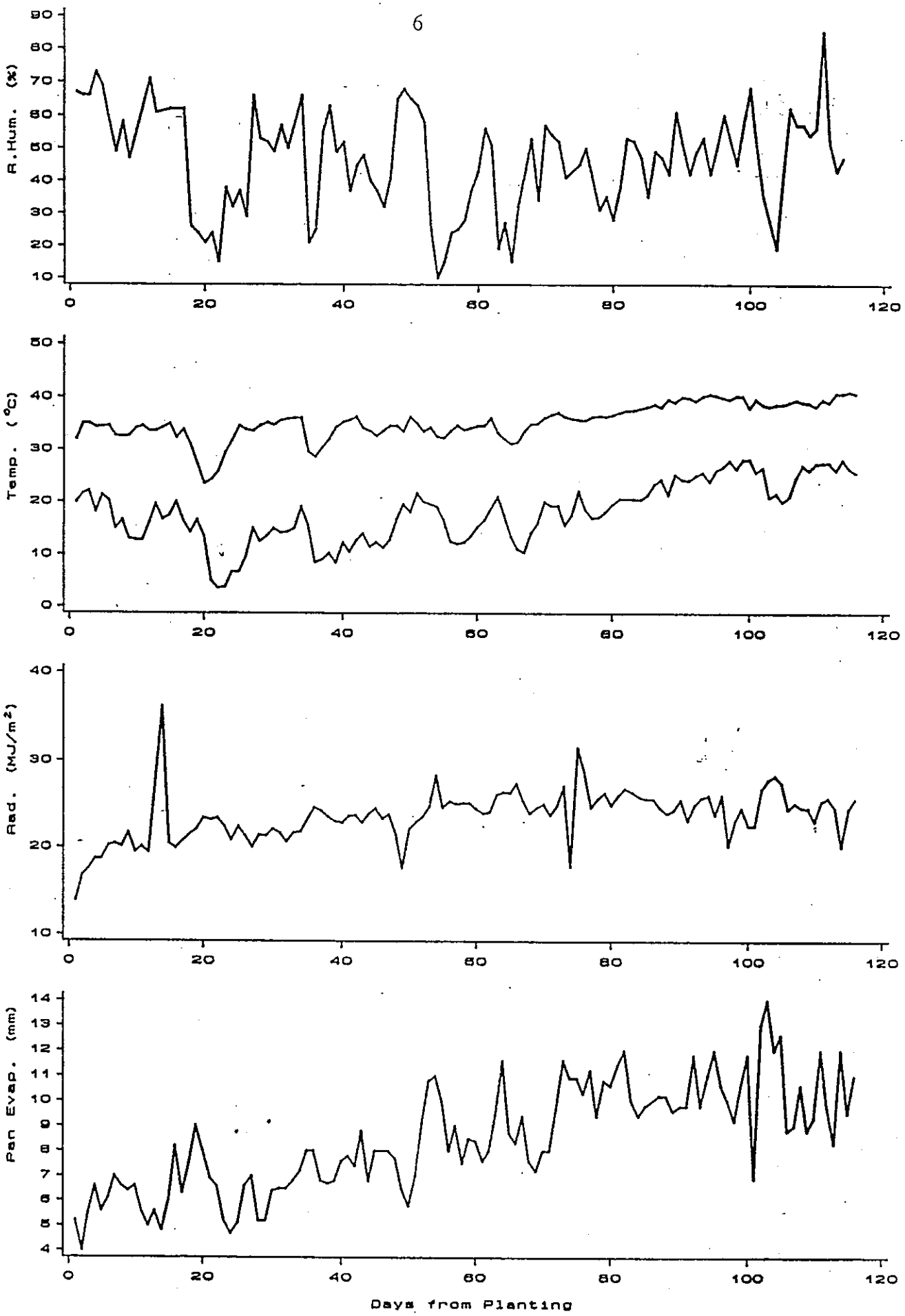


Figure 1. Relative humidity (%), daily maximum and minimum temperature (°C), incident shortwave radiation (MJ/m²), and pan evaporation (mm), at Katherine Research Station.

Additional Measurements;
Photographs were taken at each sampling date of the overall crop and of the stage of crop development.

Bulk density measurements were determined for the same soil type by J. Dymes (CSIRO) at a site 500 metres from the experimental area. The values used in this experiment are based on those of Dymes (per comm.) and are presented in Table 2.

Table 2. Bulk Density values used in calculations.

Depth Interval (mm)	0-200	200-400	400-600	600-800	800-1000	1300-1500	1800-2000
Bulk Density (Mg/m^3)	1.66	1.67	1.66	1.54	1.59	1.56	1.60

RESULTS:

Soil Moisture Content;
Figure 2 shows the amount of water applied at each irrigation event whilst Figure 3 provides cumulative irrigation amounts for each period between sampling dates.

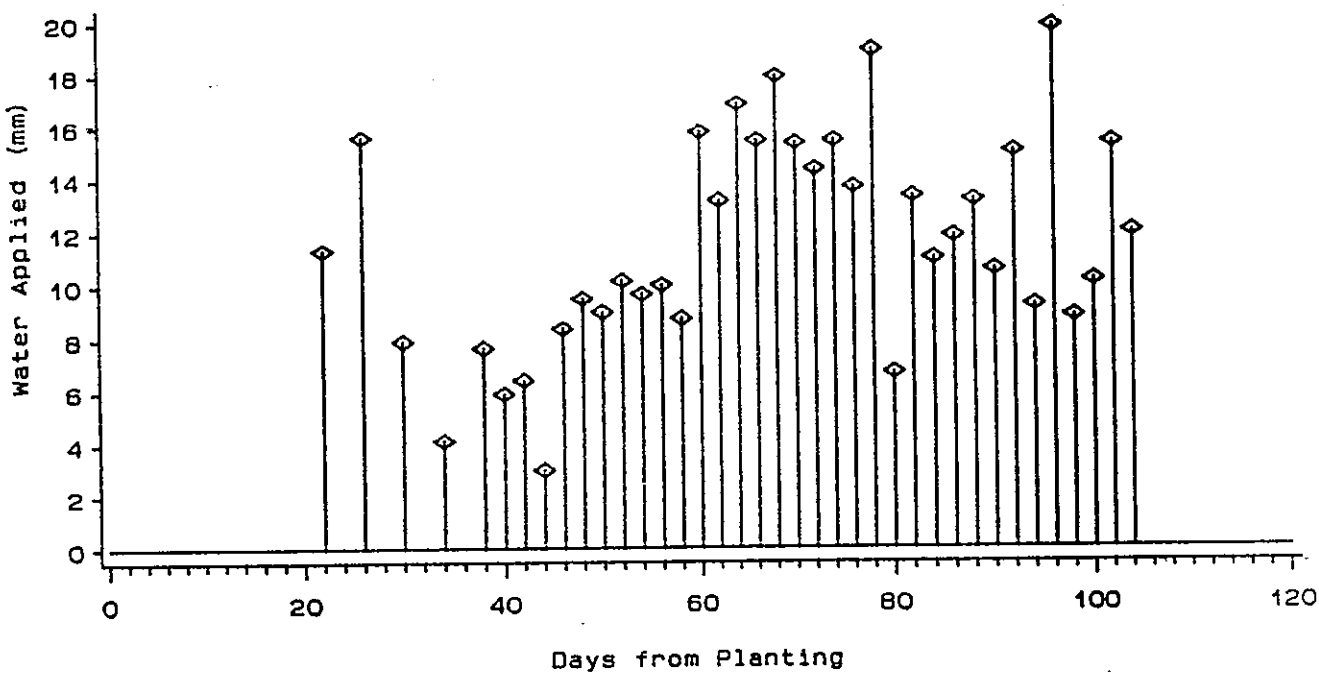


Figure 2. Quantity of irrigation applied at each irrigation event.

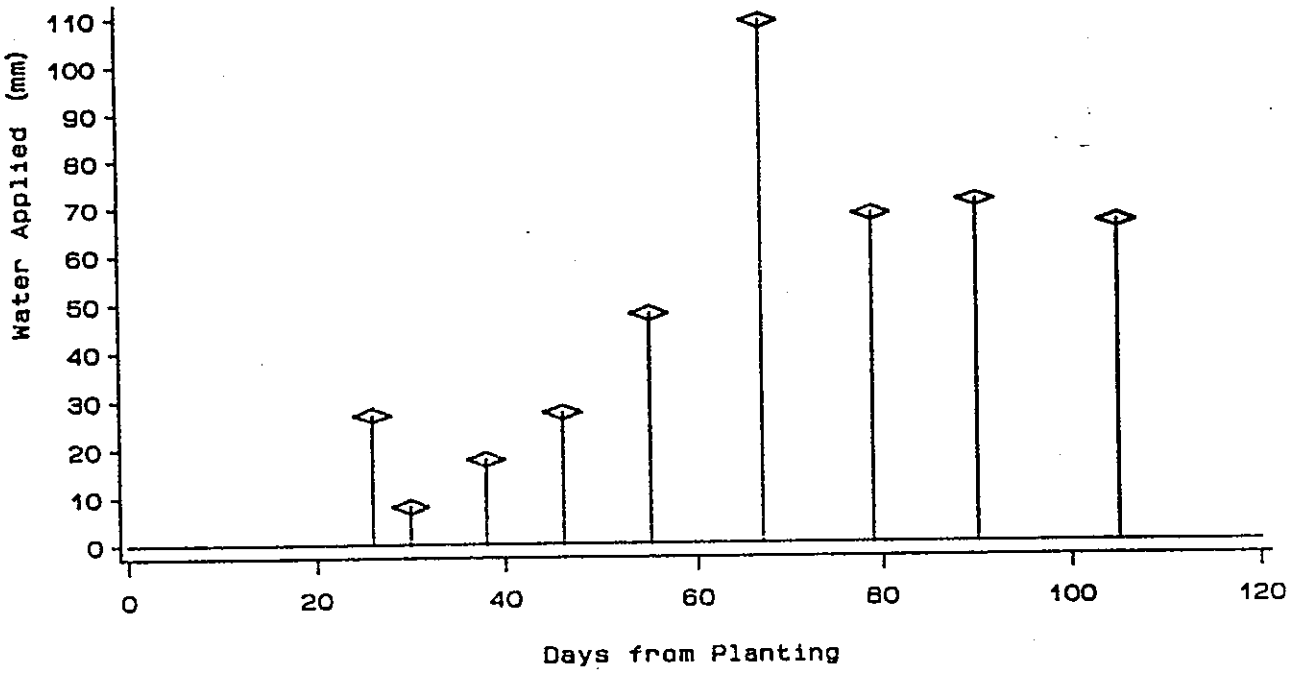
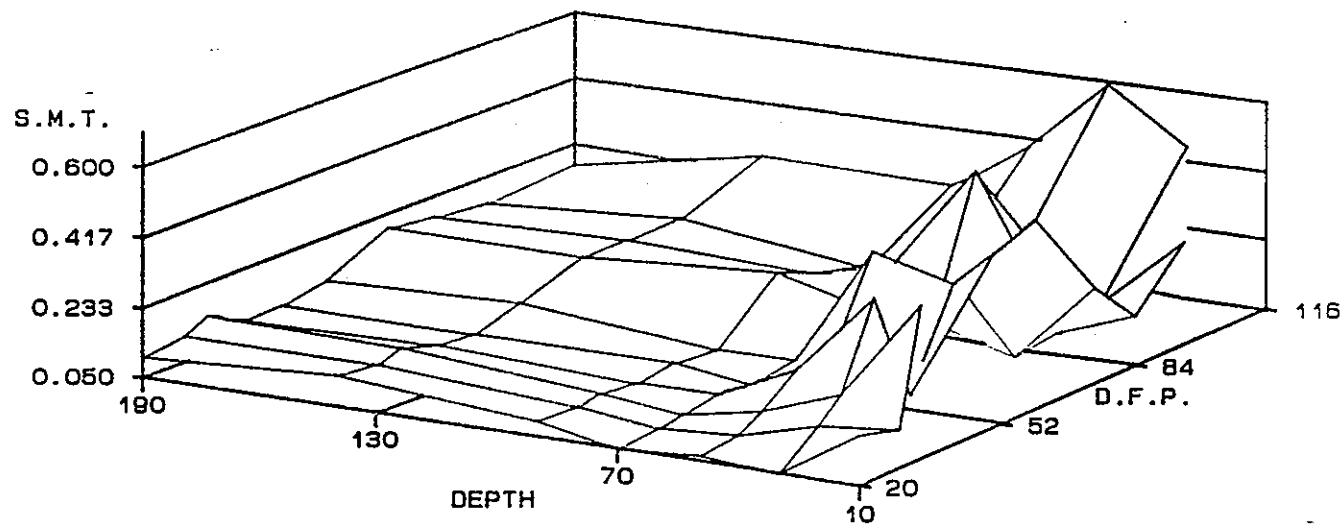


Figure 3. Cummulative irrigation for the period between each sampling date.

The mean gravimetric moisture content was used to establish soil matrix tensions for each depth at each date after planting. High tensions which occurred near the surface have been omitted from Figure 4 to enable better description of tensions at depth.



DEPTH: Soil depth in cm.
S.M.T.: Soil moisture tension in bars
D.F.P.: Days from Planting

Figure 4. Soil moisture tension for each depth and date of sampling.

Total soil moisture content (0 to 2 metres) showed a downward trend throughout the duration of the experiment. Figures 5a to 5c show the moisture content of the surface 400mm, 1m and 2m of the soil profile respectively at each sampling date.

The above information was combined in order to estimate the evapotranspiration during the ten intervals between samples.

This was calculated using the following equation:

Evapotranspiration=(Initial profile water + irrigation application) - Final profile water

Equation 1

From these figures and the known evaporation between sampling dates (Table 1) Crop Factors were calculated based on the equation:

Crop Factor= Evapotranspiration/Evaporation

Equation 2

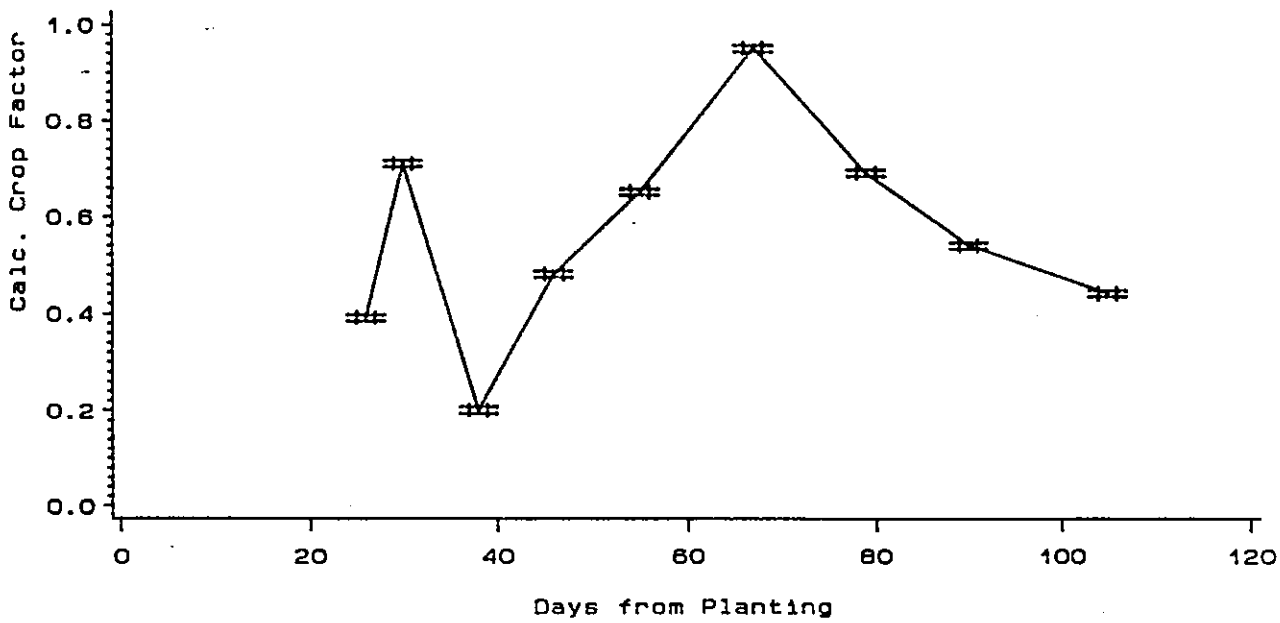


Figure 6. Calculated Crop Factor for each interval between samplings.

Fig. 5a Moisture content of top 400mm

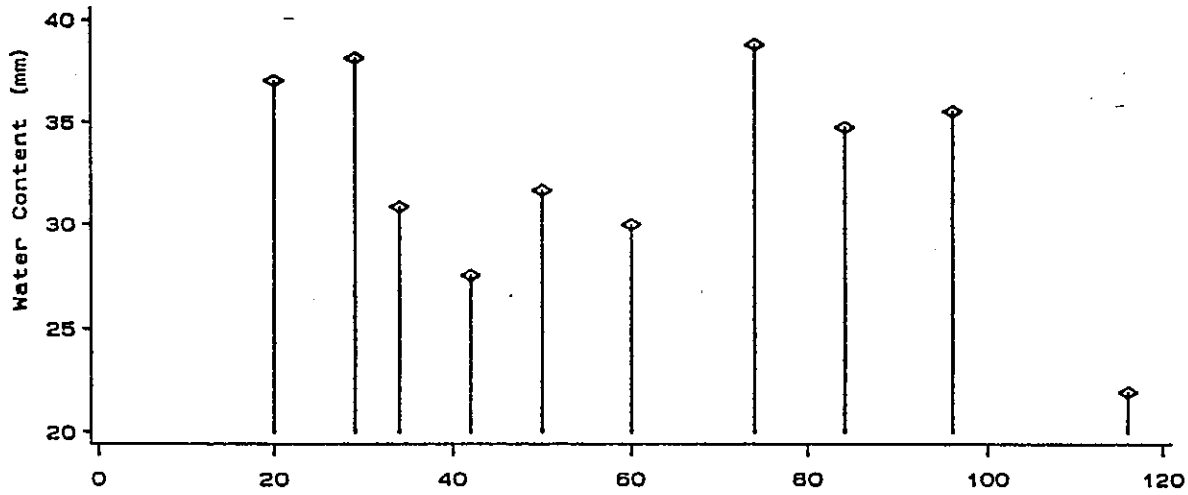


Fig. 5b Moisture content of top 1 metre

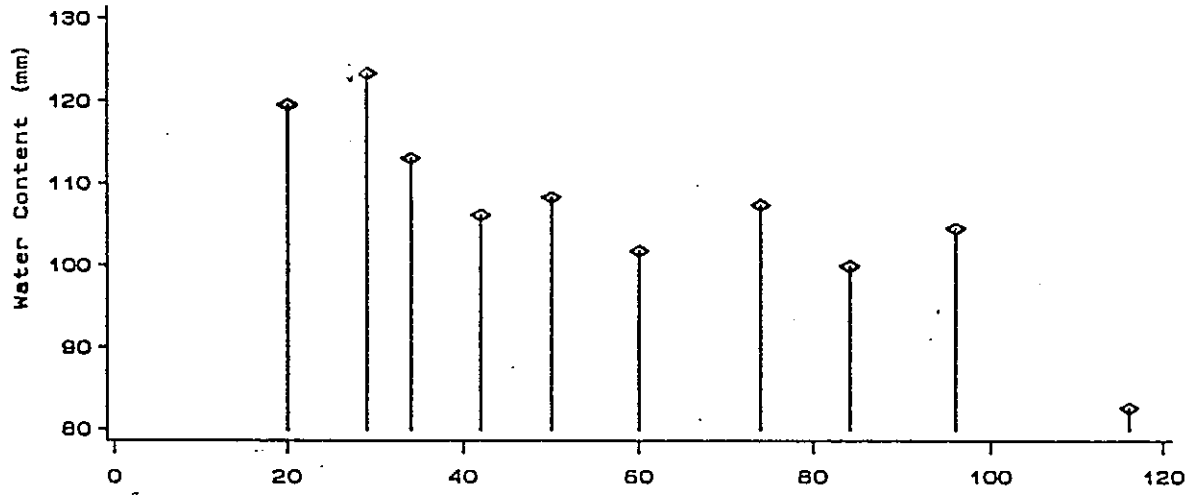
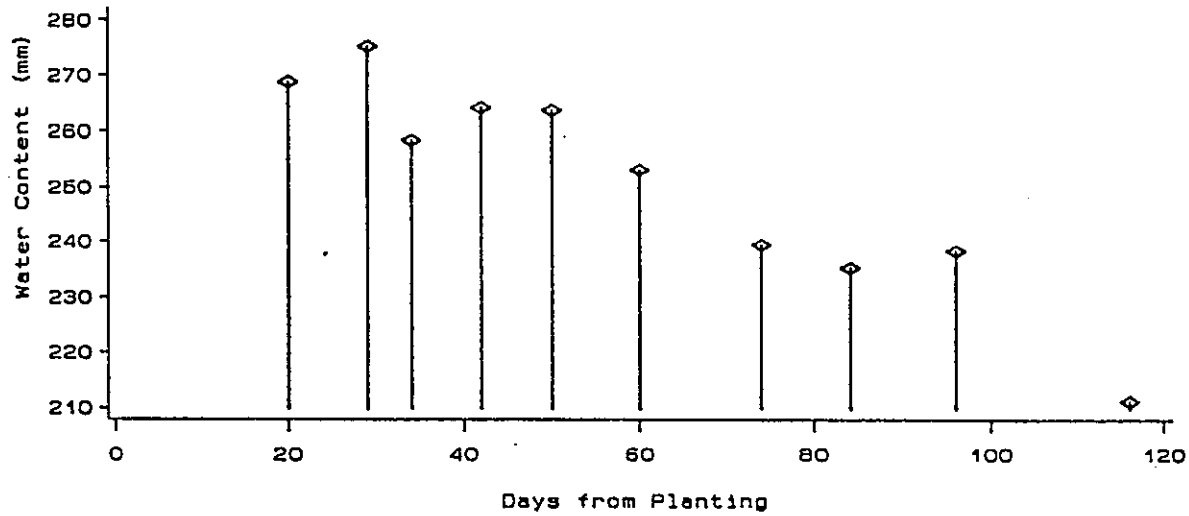


Fig. 5c Moisture content of top 2 metres



Figures 5a to 5c. Profile moisture contents for: a. the surface 400mm; b. 1m and; c. 2m at each sampling date.

Evaluation of Sampling Intensity;
On a number of sampling dates, cores were taken at more than 3 positions. Table 3 shows the effect of increased sampling intensity on the accuracy of soil moisture determinations.

Table 3. Effect of increased sampling intensity on soil moisture determination.

	For site 1, 3 & 5 (3 cores)			For Site 1, 2, 3, 4, 5 & 6 (6 cores)		
Depth (mm)	Mean	S.D.	C.V.	Mean	S.D.	C.V.
0-10	1.27	0.63	0.50	1.57	0.81	0.52
0-200	5.35	0.24	0.04	5.37	0.35	0.07
200-400	5.98	0.61	0.10	5.77	0.72	0.12
400-600	7.88	0.61	0.08	7.90	0.82	0.10
600-800	8.63	1.28	0.15	9.23	1.46	0.16
800-1000	8.63	0.93	0.11	8.73	0.49	0.06
1300-1500	9.13	0.60	0.07	9.27	0.40	0.04
1500-1800	9.67	0.72	0.07	9.63	0.74	0.08

Nitrogen;
A nitrate profile was determined on a virgin site adjacent to the crop. The gravimetric moisture content and nitrate distribution are shown in Figure 7.

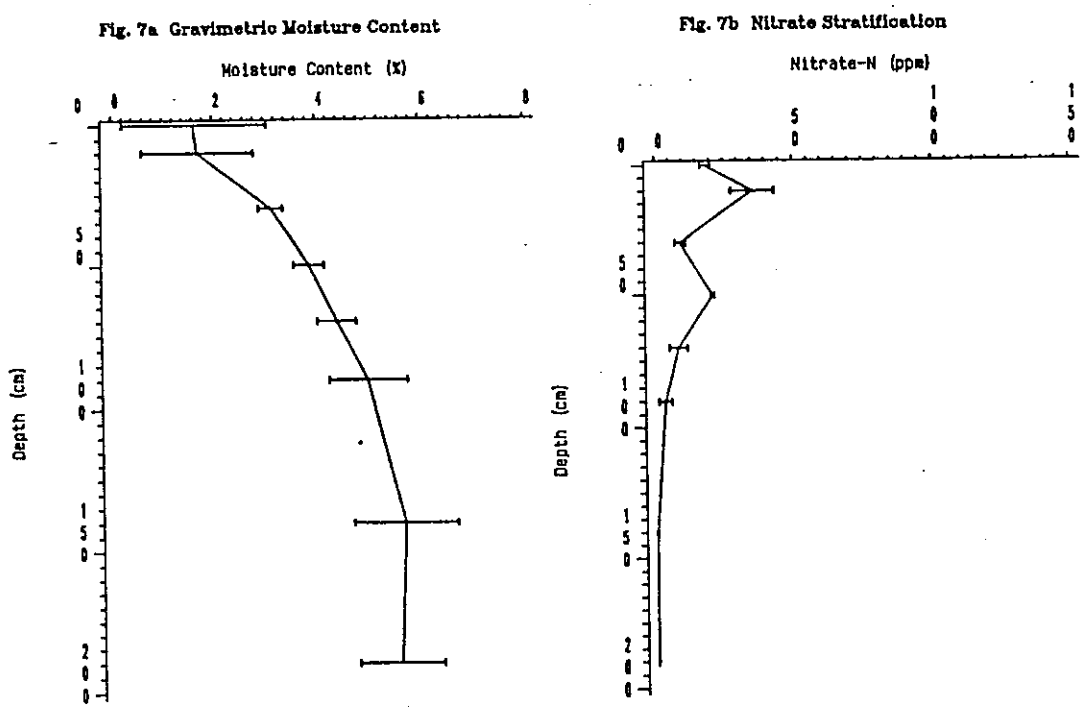


Figure 7a. Gravimetric moisture content and 7b. Nitrate stratification of a virgin site sampled adjacent to the crop on 5.11.1990.

As the experiment progressed, the nitrate concentration at different depth intervals changed. Nitrate profiles at each sampling date are shown in Figures 8a to 8j.

Fig. 8a 20 Days after Planting

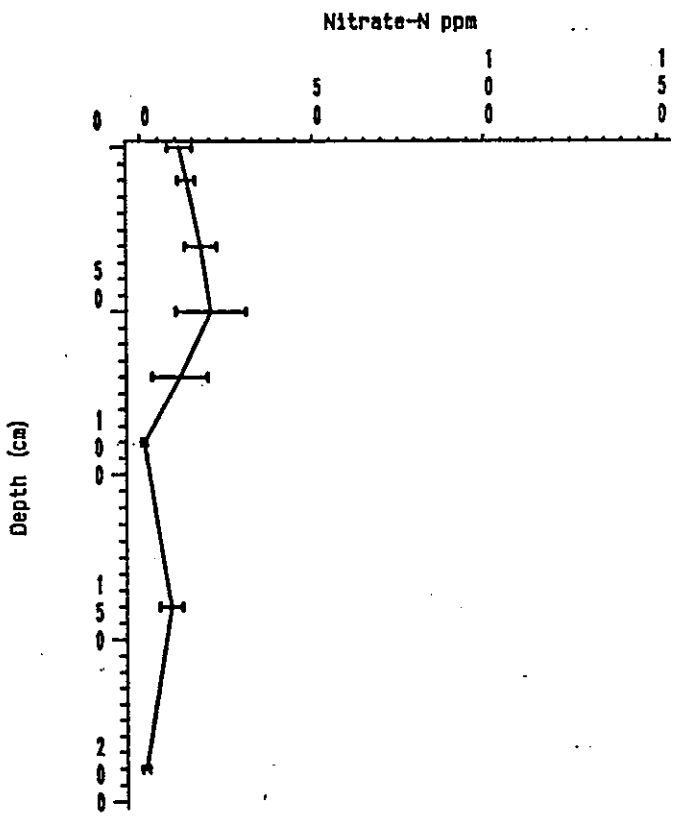


Fig. 8b 29 Days after Planting

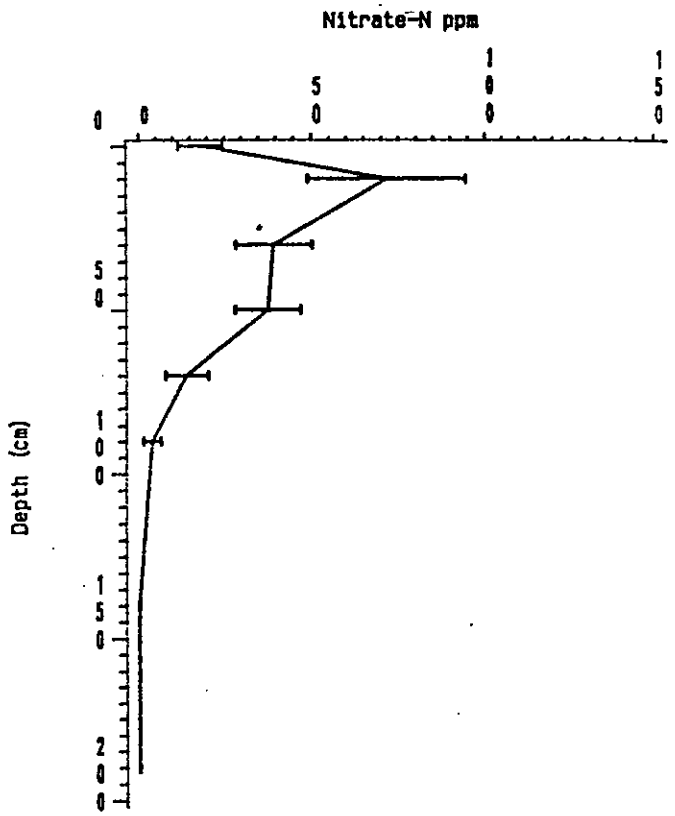


Fig. 8c 34 Days after Planting

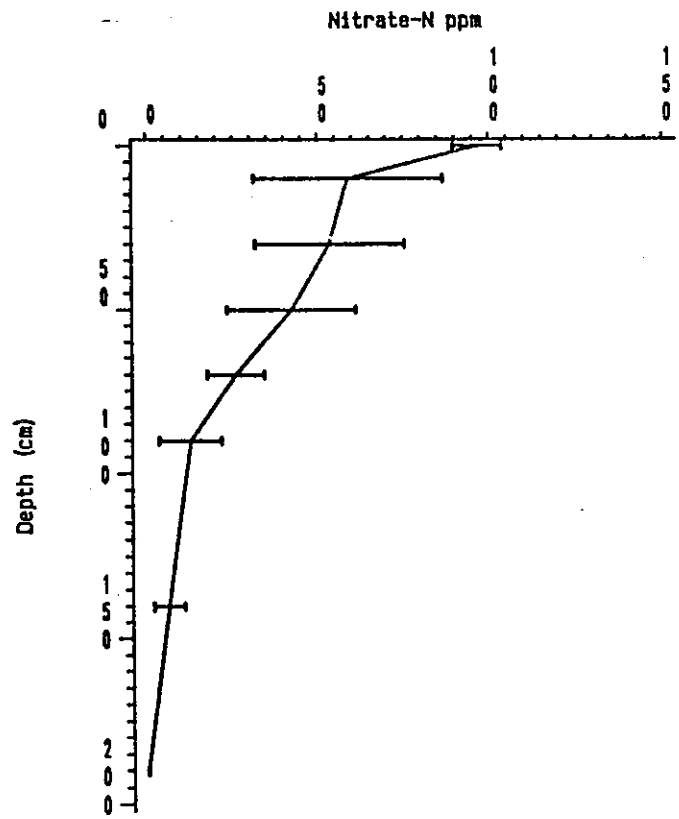


Fig. 8d 42 Days after Planting

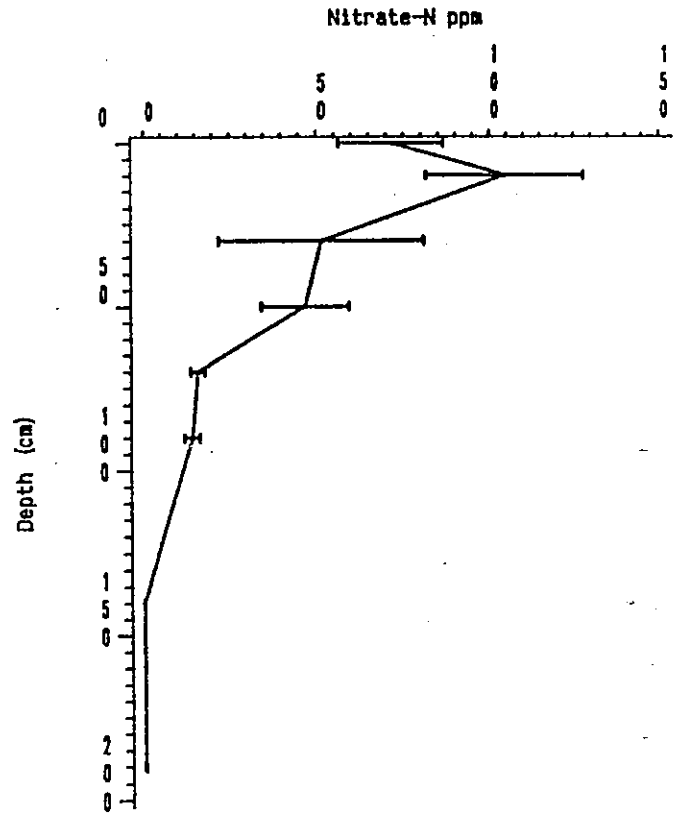


Fig. 8e 50 Days after Planting

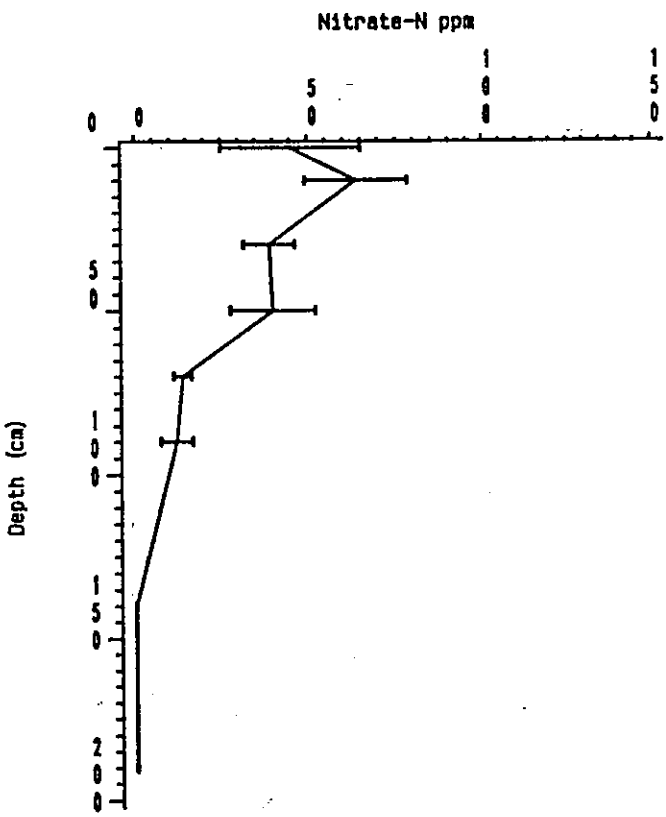


Fig. 8f 60 Days after Planting

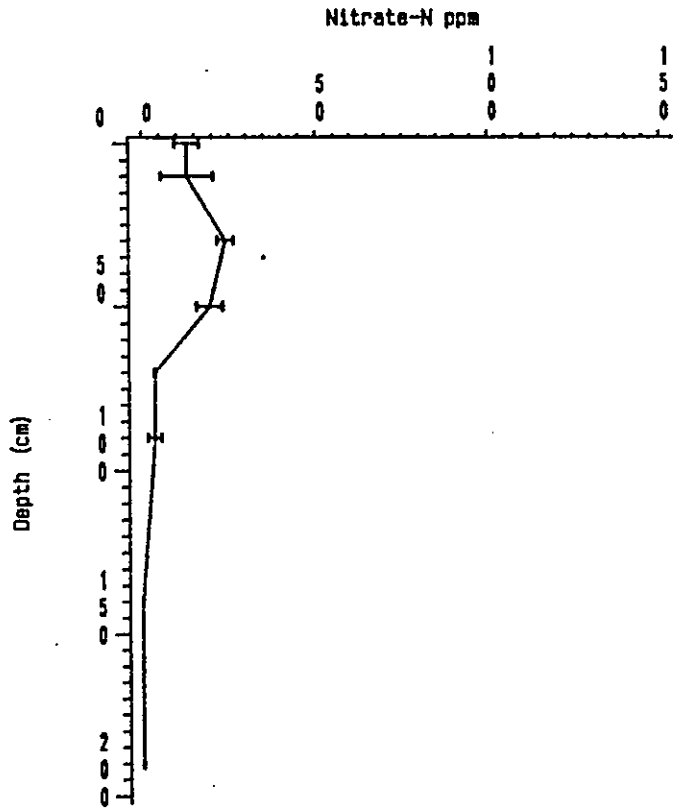


Fig. 8g 74 Days after Planting

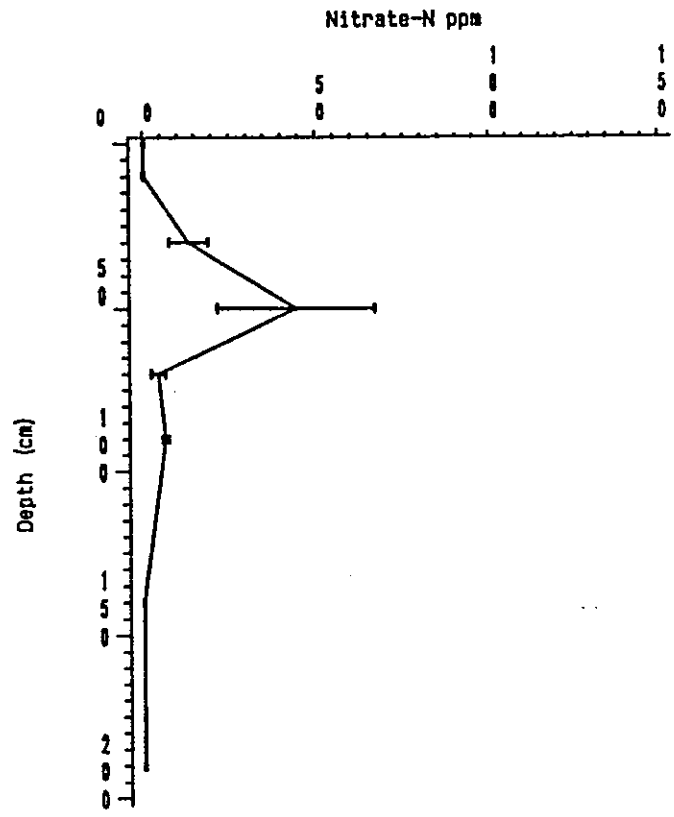
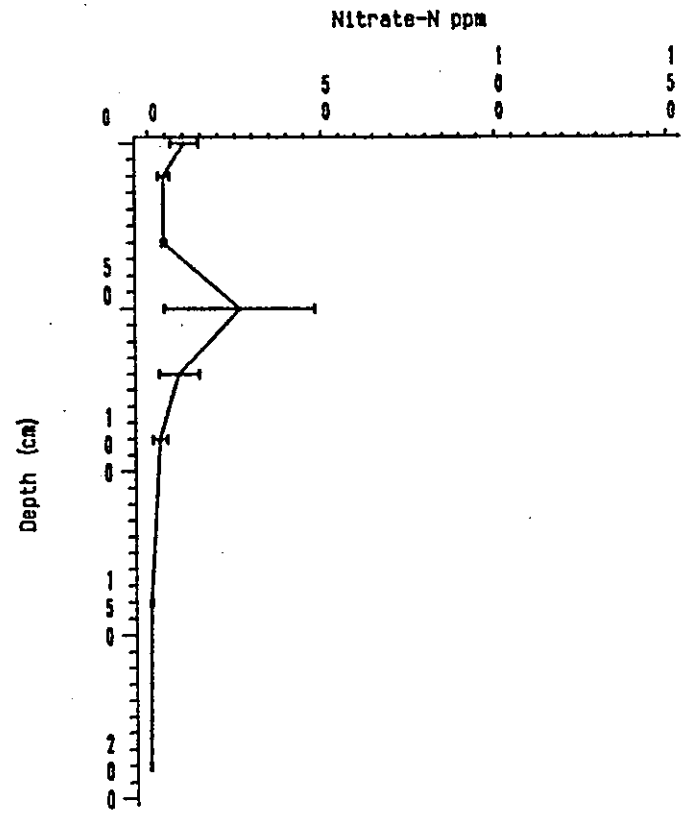
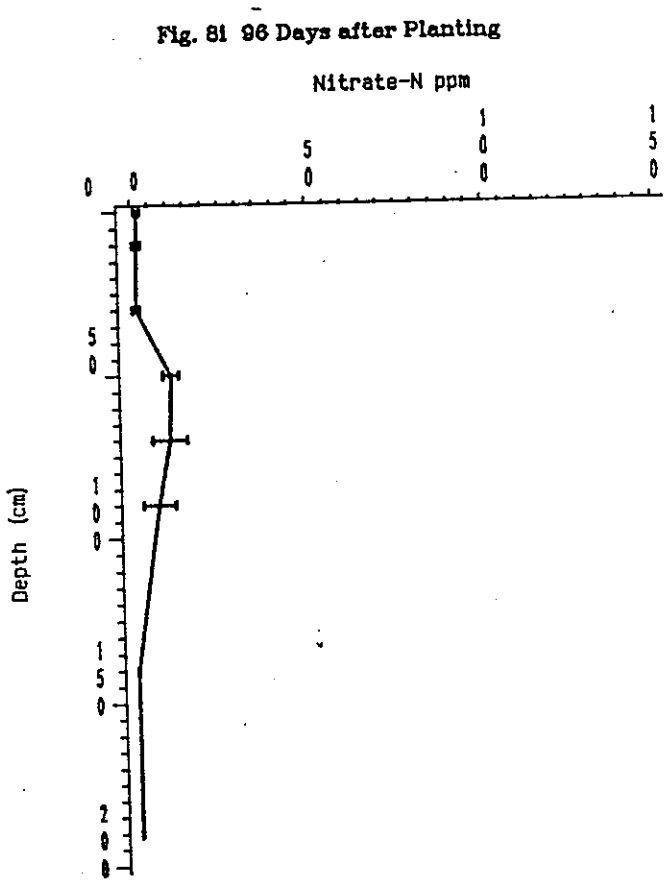
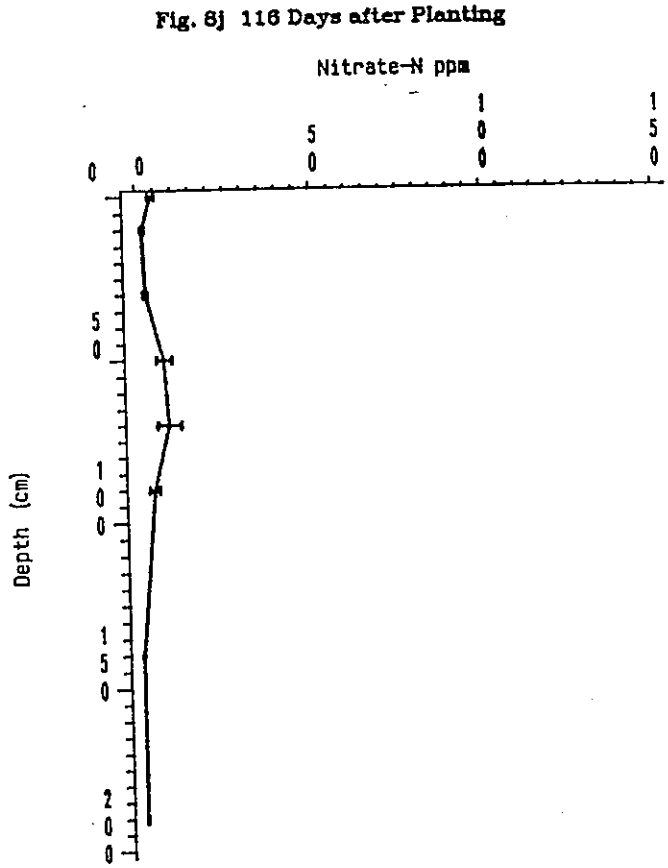


Fig. 8h 84 Days after Planting







Figures 8a to 8j. Nitrate profiles for each sampling date. Horizontal bars represent standard errors of the mean.

These figures were used to determine the actual amount of nitrate per hectare to 400mm, 1m and 2m depth at each sampling date. Figures 9a to 9c illustrate the change in nitrate content at the three depth intervals.

Crop Performance;

Flowering occurred around 37 days after planting. There was a considerable range of fruit development stages in the crop at any one time. In general, by 60 days fruit were 300mm in length and by 84 days they had almost doubled in length.

Ground cover increased from around 10 percent at 34 days to near 25 percent at 43 days. By day 50, this had increased to nearly 60 percent. Vegetative growth appeared to have largely ceased by 74 days and it was estimated that maximum ground cover was approximately 80 percent.

Fig. 9a Amount of Nitrate in the top 400mm

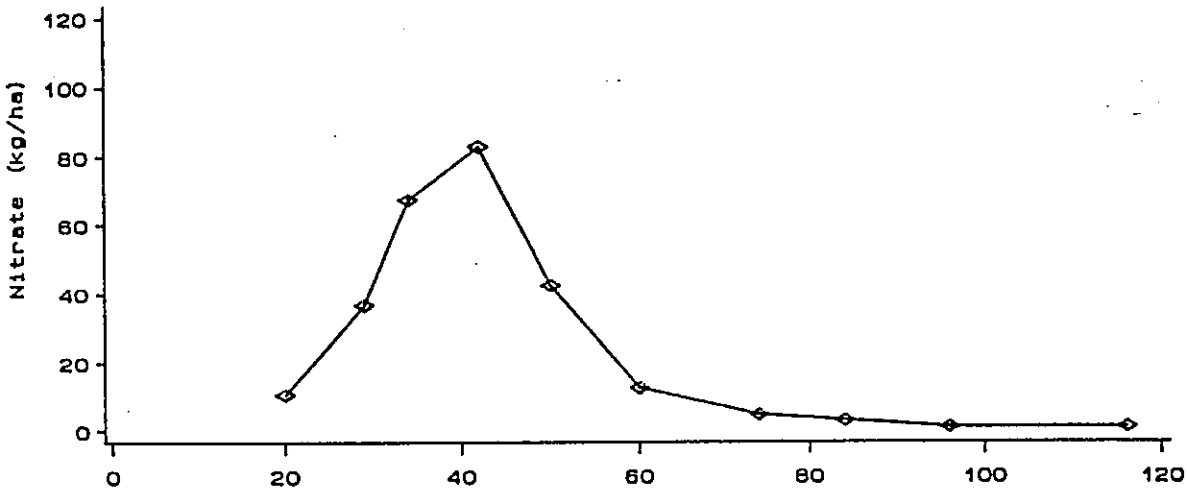


Fig. 9b Amount of Nitrate in the top 1 metre

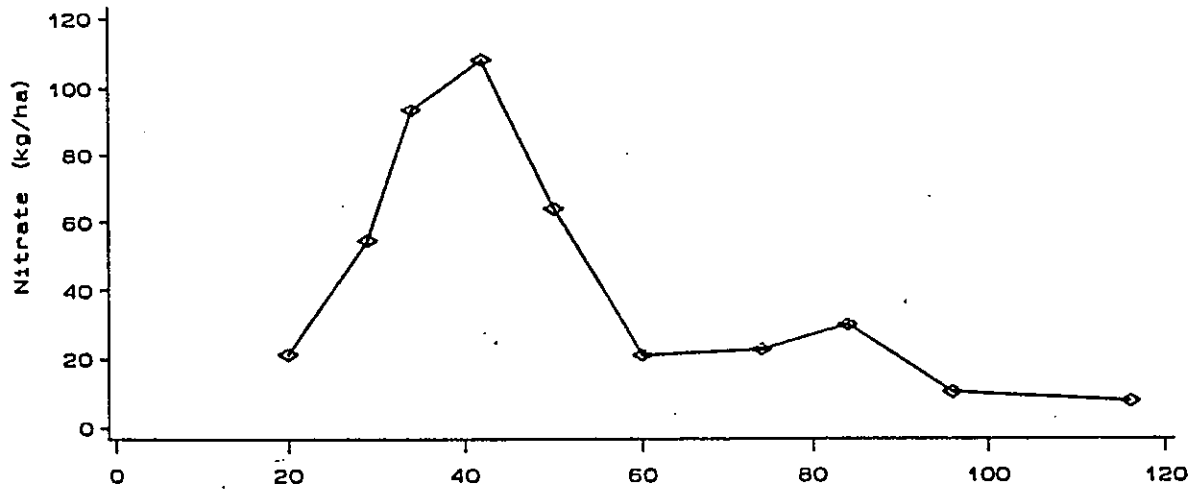
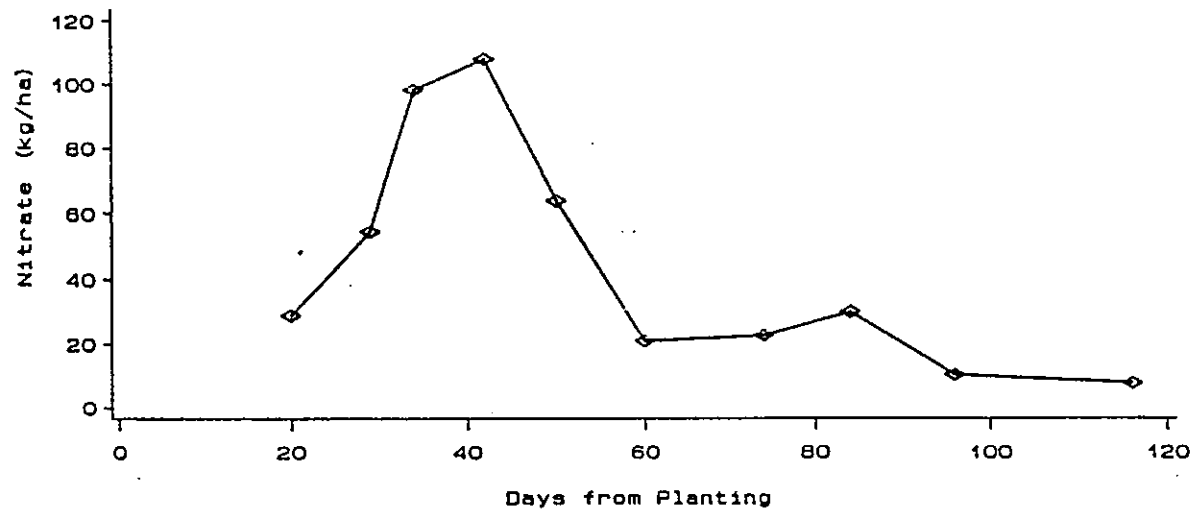


Fig. 9c Amount of Nitrate in the top 2 metres



Figures 9a to 9c. Profile nitrate contents for the: a. surface 400mm; b. 1m and; c. 2m at each sampling date.

Harvesting commenced 81 days after planting and continued until day 109.

Weekly yields and total crop yield are shown in Figure 10.

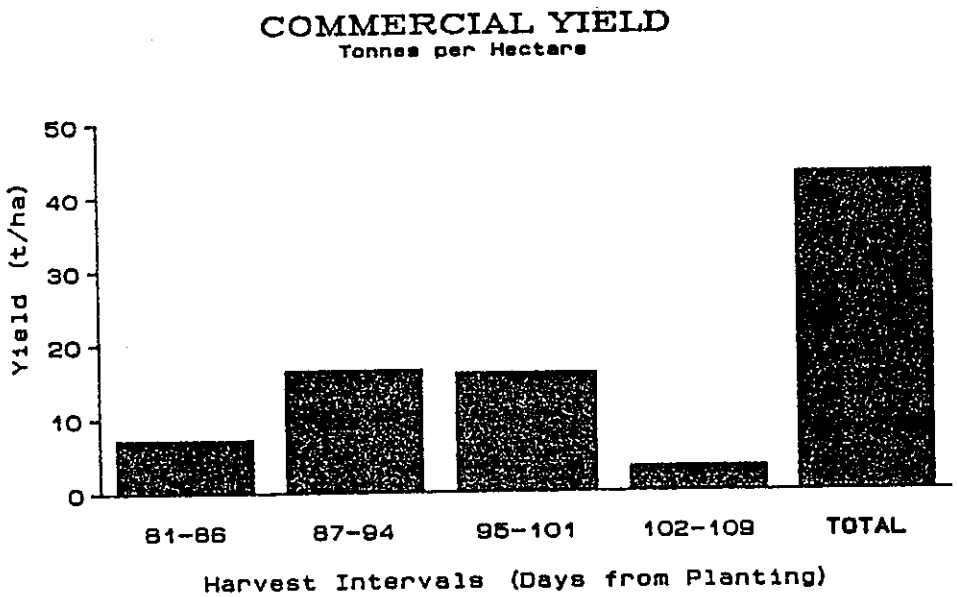


Figure 10. Harvest information.

CALCULATIONS:

An attempt was made to estimate daily crop nitrate uptake. This was based on nitrate changes in the profile, expected rates of nitrification of applied fertiliser, and expected rates of organic nitrogen mineralisation.

The amount of nitrate taken up by the plant between any two sampling dates was calculated using the equation:

$$\mathbf{PNU = SNI + An + Bn + Cn + Dn + OrgN - SNF}$$

Equation 3

where	**PNU**	= plant nitrate uptake
	SNI	= initial nitrate content of the profile
	SNF	= final nitrate content of the profile
	An	= quantity of fertiliser nitrified during the interval from fertiliser applied on day 0
	Bn	= as for **An** except for fertiliser applied on day 31
	Cn	= as for **An** except for fertiliser applied on day 45
	Dn	= nitrate added on day 64, since it was applied in the nitrate form then it was assumed to be immediately available
	OrgN	= amount of nitrate made available during the interval from mineralisation of organic nitrogen

The rate of nitrification (used to calculate **An, Bn,** and **Cn**) was determined from data presented by Wetselaar (1962b). A non-linear regression was run on this data and the following model produced: (R^2=0.9885)

$$Z = 99.73 - 101.30 \text{ Exp } (-0.0586 * T)$$

Equation 4

where **Z** = percent of applied fertiliser nitrified at a given number of days after application

T = number of days after fertiliser application

It was assumed based on the work of Wetselaar (1967) that 40 KgN/ha would be mineralised from organic nitrogen during the life of the crop, and that this would proceed at a constant rate. Hence the amount of nitrogen mineralised between two sampling dates was determined from the equation:

$$OrgN = 0.34*y$$

Equation 5

where **y** = number of days between samplings

Having calculated expected plant nitrate uptake, this figure was simply divided by the number of days between samplings (**y**) in order to obtain an estimated daily nitrate uptake. The values determined in this way are presented in Figure 11.

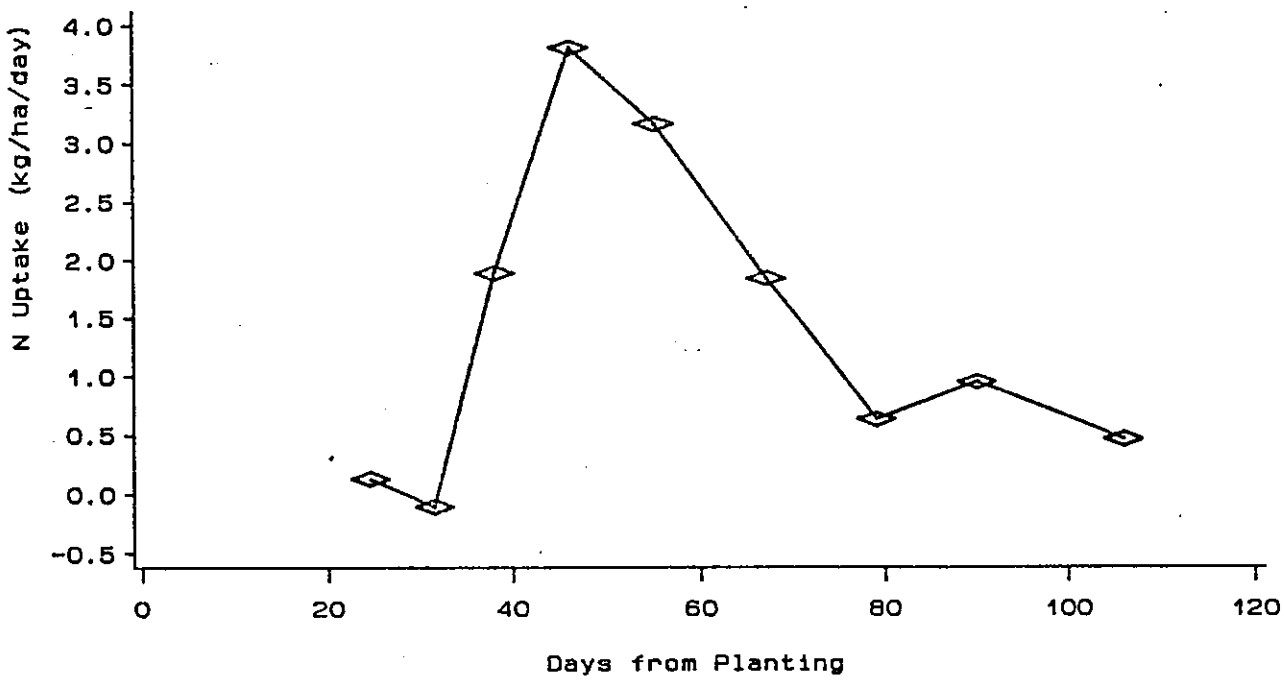


Figure 11. Predicted daily crop nitrogen uptake.

The more general form of the model for describing plant nitrogen uptake at a particular time (t) can be written:

If $t<ta$ then $A=0$
and if $t<tb$ then $B=0$
and if $t<tc$ then $C=0$
and if $t<td$ then $D=0$

then

$$PNUt = \left(SN_0 + 0.34*t + 99.73(A + B + C) - 101.3(Ae^{-0.0556(t-ta)} + Be^{-0.0556(t-tb)} + Ce^{0.0556(t-tc)}) + D\right) - SNt$$

Equation 6

where **PNUt** = plant nitrogen uptake at time **t**
SN_0 = profile nitrate content at planting (t=0)
A, B, C, D = nitrogen content of applied fertilisers
ta, tb, tc, td = time of application of fertilisers (expressed in days from planting)
SNt = actual profile nitrate nitrogen at time **t**.

DISCUSSION:

General:
Some concern may exist in using pan evaporation figures obtained some distance from the experimental site. It is generally considered that evaporation should be measured close to or even within the crop under question. To test the likely error in using figures from Katherine Research Station, evaporation data from two other sites was collated for the period of the experiment. These sites of evaporation measurement represent the only three within a 200 kilometre radius of the experimental area. From Table 1 it can be seen that evaporation varied little during the experimental period. This limited variation over an extensive area during the dry season months is not unexpected. Broad scale evaporation maps for the whole of Australia show little variation across large areas of inland northern Australia (Australian Bureau of Meteorology 1988). More detailed evaporation isopleth maps prepared for Western Australia show very little variation across a large area of the north of this state throughout the year, though particularly so during the months May to October (Luke, Burke and O'Brien 1988). In addition Kununurra, an area not particularly dissimilar to Katherine showed a coefficient of variation of monthly evaporation of only 5 to 7 percent for the months August to October. For this same period the coefficient of variation of daily evaporation was 18 percent. Similarly Slatyer (1960) in describing the climatology of the Katherine area stated that "..the relative constancy of evaporation conditions in the winter months is well illustrated."

It can be reasonably assumed that the evaporation figures used in this experiment are a sufficiently accurate representation of conditions at the experimental site.

Bulk density values used in this experiment are shown in Table 2. Many soils of the Daly Basin, in which the site used in this experiment lies, have high bulk densities. A major reason for cultivation is to lower the bulk density so as to improve water, air, temperature, and mechanical resistance relationships and to promote biological activity (Arndt and Rose 1966). Considerable discrepancy exists between bulk density determinations made by various workers for red earths within the Daly Basin and even determinations made at the same site. Values determined by various authors were obtained and compared (Arndt 1966; Myers 1972; Day 1977; Bennett pers comm.; Dymes pers comm.; Martin pers comm.; McFarlane pers comm.). Based on this, it was considered that the greatest discrepancies were the result of site histories. Values determined on uncleared virgin sites showed lower bulk densities, particularly in the surface, than those obtained from cultivated areas. That is, clearing and cultivation appears to cause a rapid increase in the bulk density of the surface soil. It is suggested that this rapid increase in bulk density under cultivation is partly responsible for the soil erosion problems that have been encountered in the Katherine area and that potential soil loss should not be calculated based on soil physical properties determined on virgin profiles. However Arndt (1966) indicated that cropping alone did not induce undesirable levels of soil compaction. Another possible explanation for the discrepancies is that surface run-off of water and organic debris and its accumulation in lower areas is a feature of this land system (Ardnt and Norman 1959; Torssell 1973). Hence differences in bulk densities obtained at relatively close sites may be the result of variations in microrelief. Bulk density sampling at the experimental site indicated that the results of Dymes (pers comm.) were suitable for use in this experiment.

Water:

Irrigation application was measured at the soil surface and later at the canopy surface as described previously. In this way, the measurements obtained represent the amount entering the soil profile, as opposed to the amount of water applied to the crop. Irrigation always occurred in the late afternoon. The precipitation rate of 7mm/hr of the irrigation system is well below infiltration rates determined for this soil type of 115, 1154 and 187 mm/hr made by Day (1977), Bristow and Abrecht (1989), and Wigston (pers comm.) respectively. It can be assumed then, that no run-off occurred and that the amount recorded in the gauges was the quantity of water entering the profile.

Gravimetric moisture content was determined to a depth of two metres. All changes in soil moisture status were assumed to take place within this surface two metres. That is, no applied water percolated deeper than two metres during the course of the experiment. If indeed percolation did occur then this amount of water would have been mistakenly added to crop water use and hence the calculated crop factor for the particular interval would be higher than it was. It can be shown that water did not percolate deeper than two metres. The chance of this occurring would be greatest when: antecedent moisture content was high; a large amount of irrigation water was applied and; crop water use was low. From Figure 2 large quantities of water were applied on days 26, 60, 68, 78, and 96. Figure 5c shows that soil moisture content generally decreased as the experiment proceeded. Profile storage had the highest probability of being exceeded around 29 days after planting, when soil moisture content was high, and a large quantity of irrigation water had been applied. Additionally crop water use would be expected to be low.

Even if it is assumed that there was no crop water use between day 20 and day 29 then soil water storage increased from 269mm to 275mm with the application of 27mm of water. In the absence of evapotranspiration the soil moisture storage would have been 296mm. Thus there had been a loss of 21mm in the 9 day period. Considering the size of plants at this stage and the percent ground covered by these plants (<10%), it is clear that this loss of water could not be due to plant transpiration alone. In fact direct evaporation from the soil surface accounts for a large proportion of evapotranspiration in early stages of crop development (Slatyer 1960). The loss of soil water by soil evaporation is most adequately described in the two-stage soil evaporation model of Richie (1972). In the first stage of this model, water is readily available for evaporation at the soil surface. The second stage requires water transport within the soil up to the surface. First stage drying is dependent on the amount of solar radiation reaching the soil surface where as second stage drying is time dependent. Slatyer (1960) provided a less complex evaluation of bare soil evaporation. For a clay loam soil at Katherine he estimated evaporation to be 0.4*pan evaporation for those weeks in which rain fell and 0.2*pan evaporation in rainless weeks. However the soil on which these factors were determined differs significantly in surface features from that on which this experiment was conducted. Dyer (1967) questioned the accuracy of using pan evaporation figures for Katherine in the late dry season and suggested that plant water requirements might reasonably be estimated from net radiation measurements. Results of Bristow *et al.* (1989) comparing two soils types at Katherine suggest that soil surface evaporation may be less severe on the loamy sand than on the clay loam. However their data did not take into account changes in soil moisture below 50mm. Soil water balance models such as that of Reddy (1983) consider evaporation from bare soil to a depth of 100mm.

Further evidence of the absence of deep percolation is provided in the nitrate profiles (Figures 8a to 8j), which are discussed in detail later.

From data presented by Ardnt, Phillips and Norman (1963) it is possible to calculate that the moisture content to a depth of two metres after saturation and three days drainage was approximately 210mm. The moisture release curves of McFarlane (pers comm.) suggest that 199mm of water would be held at 0.33 bar to a depth of two metres, however at 0.1 bar this amount would be greater by at least another 50mm. All these figures are well below the profile moisture contents measured on a number of occasions during the course of the experiment. This discrepancy suggests that neither moisture release curves developed using pressure plate apparatus, nor field capacity estimates, made after a certain period of drainage following saturation, adequately represent soil water conditions for irrigated agriculture on this soil. It is suggested that during the process of drainage, water that is normally neglected in the determination of field capacity, is available for uptake by the plant. A similar situation has been encountered on sandy soils used for irrigation in Western Australia (Luke pers comm.). Development of 'drainage functions', similar to those of Wilcox (1959), that express water availability in terms of time since last irrigation application would be one means by which to overcome this apparent discrepancy between conventional measures of soil available water and actual profile water contents. Gardner (1965) in a review of literature stated that soil physisicsts had recognised before 1955 that field capacity was an inadequate concept to describe the upper limit of available water. During the initial period after irrigation, crop water use occurs largely at the expense of free water that would otherwise have drained away (Wilcox 1960). Various methods, such

as that described by Rose and Stern (1965) have been developed to determine the drainage term in water balance equations. Wilcox (1962) defined the upper limit of available water to include drainage water and indicated that the upper limit increases as consumption use increases.

Figure 6 indicates that crop water use (expressed as a percentage of evaporation) was not a constant value throughout all stages of crop development. This suggests that crop water requirement is not simply a function of the crop, though rather of the stage of development (phenology) of the crop. From Figure 6 it can be seen that in the early stages of crop development and again toward the end of the crop, water use was low. Ignoring the sudden drop at 38 days, crop water use climbed to a peak at about 67 days and then fell off again. At peak water use almost 100 percent replacement of daily evaporation was required. In contrast less than 50 percent evaporation replacement was required in the early and late stages of the crop.

Examination of chronological photographs indicated the growth stages at which changes in crop water use occurred. The sudden change between day 20 and 29 corresponded to plants commencing to send out runners. The fall off in crop water use after day 67 coincided with fruit filling and partial leaf senescence. By day 90 a considerable amount of leaf area had been lost or was in the process of senescence and in addition some physical damage to vines had occurred in the process of harvesting. It is of interest that the calculated crop factor at the early and late stages of the crop are not particularly different from the estimated soil moisture loss values discussed by Slatyer (1960). With this in mind and considering that ground cover was not 100 percent in the early or late stages of the crop then it would seem that the changes in crop water use were even more dramatic than those discussed here.

The period of maximum water use occurred around 67 days after planting, corresponding to fruit development and large increases in fruit size. This period of maximum water use occurs in almost all crops. Muchow (1985) working with a range of grain legumes at Kununurra, found that the ratio of evapotranspiration to pan evaporation (crop factor) was similar for all plants and that the differences in evapotranspirtion between plants could be explained solely in terms of phenology. This only applied however if plants were supplied with adequate moisture and with prolonged water deficit, evapotranspiration was determined by the size of the soil water reservoir exploited by the crop.

It is important to note that it was only around 67 days after planting that evapotranspiration approached pan evaporation. Supplying irrigation at the rate of pan evaporation throughout the life of the crop would clearly have lead to deep percolation and consequently nitrate leaching. George and Cripps (1985) recommended evaporation replacement factors for a number of different vegetable crops that ranged from 1.2 to 1.8. For cucumbers, (a crop not particularly dissimilar to watermelon), they recommended replacing 1.4*pan evaporation. It is difficult to believe that such irrigation practice at Katherine would not lead to substantial losses of nitrogen via leaching.

From Figure 6 it can be seen that crop water use dropped drastically between 29 and 34 days after planting. Evapotranspiration changed from 71 percent of evaporation to only 20 percent. Examination of Figures 5a to 5c revealed that whilst the moisture content of the top 1 and 2 metres was not particularly low at day 34, the moisture content of the surface

400mm had fallen very sharply. That is, the upper surface of the profile had dried out rapidly over a 5 day period. This drying apparently created crop stress with the result that water use dropped as the plant reacted to conserve moisture. The plant was having difficulty extracting water at this moisture content. Upon replenishment of soil moisture crop water use again began to rise. From Figure 4, soil water tension (the matic potential of the soil water) was high in the surface at day 34. The tension for the interval 0 to 200mm was approximately 0.45 bar and for the interval 200 to 400mm it was 0.18 bar. Assuming the conversion of gravimetric moisture values to soil water tension is valid, it would appear that moisture uptake by the crop was severely restricted at a soil water tension well below "permanent wilting point" which is arbitrarily set at 15 bar. Soil water tension of the surface 400mm had risen further by day 42, however crop water use began to increase after this date. The tension at day 42 of the interval 0 to 200mm was greater than 15 bar. Soil water tension can reach very high levels near the surface of drying soils. In the numerical model of Ross, Williams and McCown (1985) a tension of 1500 KPa (15 bar) was reached in the 30 to 50mm interval after eight days drying under the conditions they described.

From the tension values for day 34 and 42 and the calculated crop factor for this interval, it would seem that the crop had been under quite severe moisture stress at intervals for a period of perhaps six or more days. With this in mind, it is worth noting that the crop was not showing any visible signs of stress at either day 34 or day 42. This is an important point since it illustrated that within the extremes of being waterlogged or permanently wilted crop water stress of watermelons can not be judged from crop appearance. Whilst it is possible to irrigate a crop based on the appearance of the plant and keep it alive, it is not possible to judge by sight when the plant is transpiring at a low or high rate. The author has observed on this soil type using tensiometers, that some cucurbit crops start to show signs of wilting only when the soil water tension at 300mm depth reached as high as 70 KPa (0.7 bar). Slatyer (1957) described the response of three plants to increasing soil moisture stress. His results indicated that water stress had a more pronounced effect on active processes such as elongation and vegetative growth than on passive processes such as transpiration. Consequently it should not be assumed that crop growth is not affected if water stress does not reach a level that directly reduces stomatal aperture and photosynthesis (Begg and Turner 1976). Slatyer (1957) also showed that permenant wilting percentage of any one soil was determined by the osmotic characteristics of the plant under study rather than by any soil characteristic, and consequently could vary from plant to plant.

Although permanent wilting point is arbitrarily set at 15 bar the results here suggest that moisture extraction is restricted at tensions far lower than this. From the moisture release curves of McFarlane (pers comm.) for this soil type, the change in moisture content for most of the range below 15 bar is very small. This is typical of a sandy soil and indicates that most soil moisture is available over a narrow range of tensions close to "field capacity". Profile available moisture is considered to be the difference in profile storage between field capacity and permanent wilting point. For the same soil type at a different location Day (1977) estimated that the profile available moisture was 55.6mm/m. Day (1977) also suggested that this figure was considerably higher than that determined by Ardnt *et al.* (1963). Reexamination of the data of Ardnt *et al.* (1963) indicates an available moisture content of around 28mm/m which is approximately half that reported by Day (1977). From the moisture release curves of McFarlane (pers comm.) it was

estimated that the difference in moisture storage between 0.33 bar and 15 bar for the surface 2 metres was 33.8mm/m. For the surface metre, this figure was only 28.8mm/m.

The results obtained above tend to support the contention of Slayter (1955, 1956, 1957) that as soil water tension increases toward permeant wilting point, moisture is increasingly less available to the plant and that toward field capacity, moisture is increasingly available. Denmead and Shaw (1962) have also demonstrated that when potential transpiration rates are high, actual transpiration rate falls at a lower tension than when potential transpiration is low. Thus it could be expected that on days of high evaporation, plants will experience stress even though soil moisture tension is low. This has important implications for irrigation, since if scheduling is based on profile available moisture, then some degree of moisture stress may develop prior to each irrigation event. The concept of fraction transpirable soil water as described by Sinclair and Ludlow (1986) may be more appropriate in irrigation scheduling. To determine fraction transpirable soil water it is necessary to know total transpirable soil water, which is the difference in moisture content between approximate field capacity and when transpiration rates of droughted plants have decreased to less than 0.1 of well-watered plants.

With the imposition of apparent moisture stress, somewhere around day 34, crop water use took a considerable time to recover to the level it was at 29 days after planting. It might be suggested from this that the low crop factors for the periods 42 to 50 and 50 to 60 days were the result of stress induced in the period 34 to 42 days such as had been described by Gates (1955a, 1955b). Delays in accumulation of biomass after rewatering stressed plants have been observed for cowpea and blackgram (Sinclair, Muchow, Ludlow, Leach, Lawn and Foale 1987). In a growth simulation study delaying stomatal recovery for 6 days after rewatering, predicted biomass accumulation more closely matched observed trends than when stomatal recovery was assumed to be immediate (Sinclair *et al.* 1987). However examination of soil water tension indicates that tension to a depth of 600mm remained high up until the sampling on day 74. Thus whilst crop water use was increasing after day 34, it may still have been restricted by the availability of soil moisture.

The moisture content of the top 400mm and top 1 metre decreased between day 34 and 42 whilst for the top 2 metres moisture content actually increased slightly. This suggests that even under considerable moisture stress and at this stage of crop development, moisture extraction was restricted to a depth less than 1 metre. Drainage of water from the surface metre of the profile may explain the apparent increase in soil moisture of the lower metre over this period.

It is not possible from the results obtained to describe changes in root depth with crop development. However some idea of where moisture extraction was taking place can be obtained particularly from soil water tension values. It would seem from this that moisture extraction did not take place below 200mm until day 42. At day 42 moisture extraction appeared to have taken place from the 200 to 400mm interval but no lower. Moisture extraction from the 400 to 600mm interval appeared to have taken place at day 60 but not from the 600 to 800 mm interval. By day 116 some extraction may have taken place in the 600 to 800mm interval. These are however only extrapolations and greater care needs to be taken when describing the development of extraction fronts particularly under annual crops. Despite this, nitrate removal data tends to follow the same pattern as

describe above providing further evidence that the depth of extraction increased as the crop developed. Angus, Hasegawa, Hiao, Liboon and Zandstra (1983) used a similar method for inferring the progress of root extension. They assumed that roots had arrived at a particular soil depth when the water content commenced to show a consistent decline, and found for a range of crops that the rate of root extension was between 15 to 20 mm/day. They cautioned however that it was not possible to use the water depletion method to estimate rooting depth development of irrigated crops since changes in water content of soil layers may have been due to drainage or preferential uptake. However in light of the consistent drying trend of the profile in this experiment some inference is justifiable.

Capillary rise has been described in some detail for this environment both in relation to the upward movement of nitrate (Wetselaar 1961a, 1961b; Day 1977) and in terms of water transport (Rose 1968a, 1968b; Ross *et al.* 1985). Whether increases in soil water tension are the result of water removal by roots at the particular depth interval or from capillary rise of water from that interval in response to extraction in the above depth interval is not of great importance. The important value is the depth from which water is available to the plant at a particular phenological stage. Equally important is the need to identify moisture extraction from depth when the upper part of the profile has dried out. This phenominum has been illustrated previously at Katherine, when moisture extraction/transpiration continued in a crop of bulrush millet after the surface 2 metres had dried to a soil water tension of almost 15 bar (Begg, Bierhuizen, Lemon, Misra, Slatyer, and Stern 1964). The millet was able to extract moisture from deep in the profile. Also illustrated here is the need to monitor soil moisture to a depth below which moisture extraction is expected to take place.

For most crops maximum yield is achieved when plants are grown in the absence of moisture stress. Sorghum grain yield for example is reduced when water deficit occurs prior to flowering whilst with maize yield is reduced by water deficit during both vegetative and reproductive growth (Muchow 1989). Denmead and Shaw (1960) showed that moisture stress at different growth stages in maize caused different reductions in grain yield ranging from a 21 percent reduction from stress after silking to a 50 percent reduction from stress at silking. In contrast, soybean apparently lacks a critical phase for stress and it has been suggested that this largely explains the stability of yield that exists within the context of moderate productivity (Shible, Anderson and Gibson 1975). Slatyer (1969) has also suggested that short stress periods in cereals can usually be completely compensated for by later development under adequate moisture conditions. There are however a small number of plants for which moisture stress benefits yield. Pineapple, coffee, cacao, mango and cashew all require some form of water stress in order to stimulate reproductive growth (Grierson, Soule and Kawada 1982). Low rates of water application in conjunction with high tree densities have been shown to increase fruit yields and growth in peach trees (Chalmers, Mitchell and van Heek 1981). In addition, water stress stimulated subsequent fruit growth and reduced shoot growth. It was suggested that previous water stress increased the capacity of fruit to compete for assimilate (Chalmers *et al.* 1981). Water stress may benefit yield in the case of root crops where both root-to-shoot ratio and absolute root growth can be increased (Begg *et al.* 1976). Improvements in fruit quality through the accumulation of soluble carbohydrate can be stimulated by mild stress prior to harvesting (Clements 1964). Only limited evidence could be found to show that moisture stress benefits final yield in annuals and more specifically vegetable

crops. As mentioned previously, the watermelon crop monitored in this project was one of the highest yielding, high quality crops ever produced in the region. Yet it can be seen from Figure 6 and the discussion above that the crop had been subjected to some degree of moisture stress. More work is needed to determine if moisture stress at various phenological stages in watermelon, decreases, increases or has no effect on final yield and quality.

The relationship between crop phenology and crop water use has been described for a wide range of crops. Differences in crop water use between species has been associated with different growth duration, rooting depths, root densities and rates of soil water depletion from within the root zone (Angus *et al.* 1983). Slatyer (1955) attributed differences in crop water use to root system development and the ability of plants to regulate water loss to the atmosphere. Robinson and Alberts (1989) have shown that the crop factor for bananas varied from 0.57 to 1.01 in response to seasonal conditions. Previously there has been only limited quantification of these changes for horticultural crops in the Northern Territory (Blackburn, Ramsay, Jettner and Traynor 1989). That is, crop water use has not been defined by measuring actual soil moisture changes and relating this to crop phenology. However the irrigation strategy of Blackburn *et al.* (1989) reflect changes in water use during the early stages of crop growth. This strategy was developed using soil tensiometric measurements and refined following considerable experience with the technique (Blackburn pers comm). Results discussed here are in agreement with those of Blackburn *et al.* (1989) and provide further evidence for the need to relate irrigation application to crop phenological development.

Although daily evaporation varies during the production season (Figure 1) this variation is well within the water holding capacities of soils used for irrigated horticulture. Consequently there exists considerable scope to program irrigation application even prior to crop establishment. For this to be possible more work will need to be done in relating crop factors, crop phenology and harvestable yields.

Nitrogen:

The method used for measurement of soil nitrate nitrogen in this experiment is not a standard method and requires some explanation. Initially nitrate determination was attempted using an ion selective electrode as described by Myers and Paul (1968). The electrode method has been used previously on the same soil type as used in this experiment (Day 1977). Considerable difficulty was encountered in preliminary work with an ion selective electrode for the project described here. Variability between determinations made on the same extract and poor calibration with standard nitrate solutions created the need for a more suitable and accurate method.

Merckaquant Nitrate Test Strips have been used for the last seven years in the Northern Territory for determination of plant sap nitrate status of field grown cucurbits, primarily rockmelons (Blackburn pers comm.). With soil extracts it was found that consistent results could be obtained using these strips.

Filtration of soil extracts presents a serious time constraint in the processing of samples and also increases the possibility of contamination. Centrifugation of extracts was found to successfully remove soil particles from the suspension. Centrifugation was used in the method of Ladd, Parsons and Amato (1977) for nitrate determinations. Since test strips

could be inserted directly into the supernatant whilst still in the centrifuge tube it was possible to carry out the whole process between weighing subsamples and obtaining nitrate readings within the one vessel. This greatly increased convenience and decreased processing time for samples. Consequently most samples were processed within a few hours of collection. In addition nitrate was extracted from soils at field condition. A number of authors have discussed the difficulties and errors that can arise from the handling and processing of nitrate samples.

Although the limit of detection varied slightly according to subsample size, it appeared that levels as low as 5 ppm, on an oven dry basis could be detected.

Total amount of nitrate in the profile varied throughout the life of the crop as illustrated in Figures 9a to 9c. The amount of nitrate differed little between the top metre and the top two metres, but there was less nitrate in the top 400mm on all occasions. Despite some differences the general trend of nitrate accumulation and decay followed a similar pattern.

The amount of nitrate-N in the profile reached a peak at 42 days after planting although examination of the curve would suggest that the true peak was between 34 and 42 days. To a depth of two metres, nitrate at 42 days amounted to 108 kg/ha or almost 25 kg/ha of actual nitrogen. Within the surface 400mm the amount at 42 days was 84 kg/ha of nitrate or 19 kg/ha actual nitrogen. This peak corresponds to the period of first flowering. In the 18 day period between 42 and 60 days after planting the nitrate content of the profile was reduced by 72 kg/ha in the top 400mm and by 88 kg/ha in the top metre.

A slight peak developed below 400mm temporarily at around 84 days which was subsequently removed from the profile. Nitrate removal continued even up until the last measurement at 116 days. By final harvest there remained practically no nitrate in the surface 400mm and only 8 kg/ha nitrate to one and two metres depth.

Changes in the amount of nitrate present at a particular time are determined by more factors than just crop uptake. As applied fertiliser is nitrified and soil organic matter mineralised, the amount of nitrate in the profile should increase. However the presence of a crop confounds this since it is removing nitrate from the profile. Hence even when the nitrate content of the profile is decreasing, nitrification and mineralisation may still be taking place at a high rate.

To obtain a more accurate picture of nitrate formation and removal an approach similar to that used to determine crop water use was required. By knowing the profile nitrate content between two dates and the likely contribution of nitrate from nitrification of applied fertiliser and mineralisation of soil organic nitrogen, calculation of the amount of nitrate removed by the crop should be possible. The model used to develop Figure 11 is explained in the Calculations section.

These results suggest that not only did the amount of nitrate in the profile change but that the rate of extraction of this nitrate also varied during the life of the crop. The predicted daily rate of nitrogen uptake based on Equation 6 is shown in Figure 11.

From Figure 11 it can be seen that nitrogen extraction climbed sharply after about day 35 to a peak extraction of 3.8 kg N/ha/day for the period 42 to 50 days after planting. For the interval 29 to 34 days, nitrate uptake according to the model was -0.1 kg N/ha/day, which indicates some inadequacy in the model. However for this five day interval, the nitrogen involved amounted to only -0.5 kg N/ha. As discussed above it was during this interval that the crop experience moisture stress. Gates (1957, 1964) has shown with tomato plants that during water shortage nutrient uptake virtually ceases. Thus whilst nitrogen uptake would not have been negative during the period 29 to 34 days, it may well have been negligeable. This would also explain why nitrogen uptake fell between the first and second sampling intervals and then recovered sharply. By comparing Figure 11 with Figures 9a to 9c it is possible to estimate at what dates nitrogen extraction was limited by profile nitrate availability. From this it is suggested that nitrogen uptake was not limited by the availability of profile nitrate at least between the interval 29 to 50 days when peak extraction rates were predicted.

It was assumed that mineralisation of organic nitrogen continued at a constant rate during the course of the experiment. Stanford, Frere and Vander Pol (1975) measured soil nitrogen mineralisation over the range 5°C to 35°C and found that the mineralisation rate did not vary with fluctuations in temperature. Although soil temperature would be expected to exceed 35°C for this soil even under irrigated conditions (Kalma 1971) such conditions would only be expected to occur in the surface few centimetres (Rose 1968a, 1968b; Bristow *et al.* 1989). A similar argument can be forwarded to negate the inhibitory effect of soil drying on organic nitrogen mineralisation. Wetselaar (1968) working with a clay loam and sand from the Katherine region found that nitrate formation ceased at tensions of 24.3 and 50 bar respectively. Thus whilst no nitrate is formed in the absence of irrigation in the dry season (Wetselaaar 1961b) it is unlikely that soil water tension would be sufficiently low to inhibit nitrogen mineralisation for extended periods between irrigations. Ladd *et al.* (1977) found that intermittent drying and wetting of soils stimulated mineralisation but that qualitatively the pattern of change was similar to soils kept under uniformly moist conditions.

As with mineralisation of soil organic nitrogen, it was assumed that conditions during the growth of the crop would not have inhibited the nitrification of applied fertiliser. Conditions of high soil water tension existed in the surface 10mm sample collected at each sampling date. It has been shown however that on this soil type applied fertiliser moves further below the surface than on the heavier Fenton clay loam (Wetselaar 1962; Day 1977). Hence applied fertiliser moves into an environment more favourable for nitrification. Wetselaar (1962) has suggested that this is largely the result of lower total cation exchange capacities associated with the sandy surface.

The organic carbon content of the surface 150mm was determined to be 0.41 percent at a site 150m from the experimental area, that had been cleared but not cropped. Data presented by Day (1977) for the same soil type at a different location showed that the C:N ratio of the profile ranged from 20 to 22.5 in the surface 150mm and remained constant at 15 for depths below 150mm. The extent of immobilisation of nitrogen varies according to the amount and ease of decomposition of the organic matter present. If the C:N ration of organic matter is 20 or less, then it is generally considered that biological immobilisation will not take place to any great extent (Allison 1966). Because of the low C:N ratio of

the soil used in this experiment it is reasonable to assume that immobilisation would not be of any significance. The results of Wetselaar (1967) on the mineralisation of organic nitrogen support this contension.

It was assumed that 100 percent of applied fertiliser was converted to nitrate during the course of the experiment and either taken up by the crop or added to the profile. The rate of nitrification was estimated according to data presented by Wetselaar (1962). Although Wetselaar's data was determined for nitrification of ammonium sulphate on the Venn sandy loam, the results of Wetselaar, Passioura and Singh (1972) using the heavier Fenton clay loam indicated that nitrification of urea proceeds at a faster rate than that of ammonium sulphate. Eno and Blue (1954, 1957) showed that where rapid nitrate production was required on slightly acid fine sands or loamy fine sands, anhydrous ammonia or urea were better sources of nitrogen than ammonium sulphate. Conversely, they suggested that under alkaline conditions ammonium sulphate would be a better source. However Whitehouse and Leslie (1973) indicated than on an alkaline clay soil the effects described by Eno *et al.* (1954, 1957) for closed incubation experiments were of little significance under field conditions.

Application of irrigation water at Katherine is known to significantly increase soil pH. Consequently it may be that under irrigated conditions nitrification of ammonium sulphate proceeds faster than that of urea because of the ability of the former to restore soil pH to a level at which nitrification can proceed. More work is needed in this area to determine at what rate nitrification proceeds for varies nitrogen forms under irrigated conditions at Katherine. For this experiment it will be assumed that nitrification of both ammonium sulphate and urea proceed at the same rate as described in Equation 4.

The form of nitrogen used as fertiliser has been recognised as an important consideration in irrigated horticulture at Katherine. Although no experimental work has been done in this area, most growers apply nitrogen in the form of ammonium sulphate. Soil pH can reach between 8 and 9 under the influence of irrigation. The diffusion of sulphate ions following the application of ammonium sulphate has an acidifying effect on the soil (Whitemore *et al.* 1973). Wetselaar *et al.* (1972) have also demonstrated the acidifying action of ammonium sulphate in comparison to urea. Nitrification of ammonium sulphate was found to be slower than that of urea since it created a pH environment unsuitable for nitrite formers and consequently nitrate formation was slower (Wetselaar *et al.* 1972). This situation may not however prevail under conditions at Katherine since with an already alkaline soil the effect of ammonium sulphate may be to lower the pH to a level in which nitrification is favoured, rather than to reduce it below a level at which nitrification occurs.

In this experiment the majority of fertiliser nitrogen was applied in the form of urea, however, as described above the land had never been irrigated prior to this experiment. This important relationship between soil pH, form of nitrogen used, and rate of nitrification may partly explain the difficulties some growers have encountered in managing new land at Katherine. That is, whilst urea may be a suitable form of nitrogen in the first season of cropping and even perhaps early in each season, acceptable results may not be achieved after a few seasons of irrigation.

Whilst the importance of organic nitrogen has long been recognised in Northern Territory wet season cropping systems, in irrigated horticulture it has been virtually ignored. Green manure crops are grown on horticultural land during the wet season (December to March) and incorporated prior to planting. Most soils are course textured and it could be expected that mineralisation of the incorporated organic matter would be rapid (Broadbent 1962). Wetselaar (1967) has shown that around 12.5 percent of total organic matter is mineralised in the first season after cultivation on Venn sandy loam at Katherine. This figure dropped to around 5 percent in the following years. No work has yet been done on the breakdown of green manure crops at Katherine and their subsequent release of nitrogen. Based on the work of Jenkinson (1966, 1971) it could be expected that a large proportion of the added organic matter would remain undecomposed during the cropping season following incorporation. Myers (1983) working under rainfed conditions found that incorporation of large quantities of grain sorghum stubble only slightly reduced the nitrogen uptake of subsequent crops, however he did not measure the decomposition of the added organic matter. Wade and Sanchez (1983) were able to obtain 90 percent of the yield of crops receiving complete inorganic fertilisers simply through the addition of green manure residues immediately prior to planting. Their results also suggested that organic nitrogen was as available for plant uptake as inorganic nitrogen.

In this experiment, the only addition of organic matter was that associated with initial clearing of native vegetation. Based on the work of Wetselaar (1967), Day (1977) and Dymes (pers comm.) it was assumed that 40 kg N/ha was mineralised from organic nitrogen over the 116 day period of measurement. This represents 26 percent of the nitrogen added to the system. In future great account will need to be taken of the contribution of organic nitrogen to crop needs.

An initial profile sample prior to fertiliser application and planting was not taken. Nitrate profiles can be determined at any time during the dry season provided no water is added to the soil during this period (Wetselaar 1961b). Comparison of Figure 7a and Figure 8a supports this assumption with only slight changes in nitrate distribution at depths above the 400 to 600mm interval. In the virgin profile it can be seen that the top 10mm had a lower nitrate concentration than the 0 to 200mm interval, and that the interval 200 to 400mm was also lower in nitrate than the interval above it. The capillary rise of nitrate under drying as described by Wetselaar (1961a, 1961b) accounts for these observations. Similarly the peak concentration in the 400 to 600 mm interval is explained in terms of leaching (Wetselaar 1962). The shape of the nitrate profile obtained here is very similar to that described by Wetselaar (1967), for a site less than 1000m away. The nitrate content of the profile at 20 days after planting (28.8 kg/ha) differs little from that of the virgin profile (25.7 kg/ha).

From the results presented here, it is not possible to determine the amount of nitrogen "lost" from the system. It is unrealistic to assume that the only loss of nitrogen from the system was in the harvested fruit. Myers (1978) in work at Katherine demonstrated the importance of the nitrogen form in reducing losses from the system. He showed that broadcast urea and ammonium fertilisers were not particularly susceptible to volatilisation and were better able to retain nitrogen within the root zone than nitrate which was more susceptible to leaching. In a study with tagged nitrogen (^{15}N) it was found that plant uptake from urea was lower than that from ammonium sulphate and ammonium nitrate (Myers 1979).

Work previously conducted in this environment has discussed possible mechanisms of nitrogen loss. Myers (1978) concluded on the basis of his results and those of Wetselaar (1962) that nitrogen fertiliser is not particularly susceptible to loss via volatilisation. The use of tagged nitrogen fertiliser enabled better determination of the reasons of low crop recovery of nitrogenous fertilises at Katherine and in a later experiment using this technique Myers (1983) suggested that denitrification, volatilisation of ammonia and leaching of nitrate were all possible pathways of nitrogen loss. Considerable disagreement exists in the literature then as to the importance of these pathways, particularly volatilisation of ammonia. This may be partly explained in terms of experimental procedures. Those experiments conducted at Katherine using supplementary irrigation would be more susceptible to volatilisation of ammonia because of the influence of irrigation water in raising soil pH. Many authors have demonstrated that loss of nitrogen by ammonium volatilisation increases with soil pH, concentration of ammonium fertiliser, decreases in moisture content, and increases in temperature (Allison 1966). Wetselaar, Jakobsen and Chaplin (1973) demonstrated the loss of ammonia under alkaline conditions on soils at Kununurra. Under greenhouse conditions volatilisation losses as high as 35.3 percent from surface applied urea were observed. Wright and Catchpole (1985) showed that the large losses of ammonia into the atmosphere from surface applied urea could be reduced were nitrification of applied ammonium lowered the pH of the soil.

Smith and Chalk (1980) demonstrated that gaseous loss of nitrogen occurred when soil pH was greater than 7.5 and reported losses as high as 16.5 percent of applied ammonia within 28 days of application to a calcareous soil. As mentioned previously, urea has been used in irrigated horticulture at Katherine with often unsatisfactory results. Volatilisation of applied nitrogen may partly explain this.

Denitrification occurs under anaerobic conditions and is often cited as the cause of unidentified losses of N from agricultural systems (Kissel 1976). Wright *et al.* (1985) found that the loss of tagged nitrogen from irrigated sorghum was about 27 percent of the amount applied. This loss was attributed to denitrification within structural units of the soil since there was no evidence for leaching and only limited volatilisation of ammonia.

In this experiment denitrification would appear an unlikely mechanism of loss because of the coarse soil texture and the fact that soil moisture was directly controlled by irrigation and not rainfall. The air entry potential of this soil has been determined at 0.02 J/kg (Bristow *et al.* 1989), and it appears unlikely that anaerobic conditions would exist at any stage during crop growth.

If there was any loss of nitrogen from the system then the only likely pathway would have been via volatilisation of ammonia.

From Figure 8a to 8j it can be seen that virtually no nitrate moved below the 600 to 800mm depth interval. By day 116 less nitrate remained (7.7 kg/ha) than was present in the virgin profile before planting (25.7 kg/ha). These results indicate that no leaching occurred, and that the crop made use of practically all the nitrate available to it.

The nitrogen content of fruit was determined to be 1.81 percent on a dry weight basis (De Souza pers comm.) At a moisture content of 93 percent, this would represent the removal of 1.3 kg N per tonne (fresh weight) of fruit. With a yield of 42 tonnes/ha, approximately

53.2 kg of N would be removed in the harvested fruit. Consequently about 46 percent of added fertiliser and only 34 percent of nitrogen estimated to have been made available to the crop, was removed from the field in the fruit.

Present fertiliser recommendations for watermelons grown at Katherine are based largely on work carried out at Coastal Plains Research Station near Darwin (Blackburn pers comm.). These suggest that 75 percent of the nitrogen should be applied prior to fruit set with a total of 50 kg N/ha injected. This is in addition to approximately 30 kg N/ha applied in the base fertiliser at planting. Recent result indicated for the range 35 to 80 kg N/ha injected maximum yield was obtained at 40 to 50 kg N/ha (Blackburn pers comm.). However no account was made for the contribution of organic nitrogen and at the reported yield of 126 tonnes/ha, approximately 200 percent of the applied fertiliser would have been removed in the harvested fruit.

Results obtained here indicate the need to take account of the form of nitrogen used, the rate of nitrification of applied nitrogen, and the contribution from organic nitrogen in making fertiliser recommendations for this crop.

Root extraction has been discussed previously in relation to soil water. Figures 8a to 8j provide further evidence for increasing rooting depth with crop age. Nitrate concentration reached a peak in the 0 to 200mm interval of about 100ppm at 42 days after planting. A steep reduction of nitrate occurred between 42 and 60 days with an increasing proportion of this taking place at depth. Thus as the crop aged and the nitrate concentration decreased, nitrate was recovered from deeper in the profile. The results suggest that at day 50, nitrate was being extracted as low as the 400 to 600mm interval and that by day 60 extraction had occurred from the 600 to 800mm interval and possibly from 800 to 1000mm. These extraction fronts for nitrate are in general agreement with those for soil water although they suggest possibly deeper root development than does soil water.

Splitting of fruit shortly before harvest has virtually destroyed complete crops of watermelon in the Katherine district. This has been associated with late application of nitrogen or rapid changes in soil moisture. However splitting also occurs in crops to which no nitrogen has been applied since fruit set. In an unpublished survey of farms in the Katherine area, the author has identified large quantities of nitrate at depth between 0.5 and 2.8 metres immediately after final harvest for a range of crops and management practices. It is hypothesised based on the continual extraction of available nitrate and the increasing development of root depth with crop age suggested in these results, that fruit splitting in watermelon (and possibly other crops) results from recovery of previously leached nitrate by roots intercepting these accumulations late in the crops development.

Nitrite (NO_2^-) was detected on a number of occasions at various depths during the course of the experiment. It was not possible to determine the concentration of nitrite however based on the intensity of the photochemical reaction considerable quantities may have been present. Nitrite accumulation has never been recognised as a possible problem in Northern Territory horticulture. Considerable work relating to nitrite has however been undertaken at Kununurra (Wetselaar 1973; Wright and Catchpole 1985; Wright, Foale and Charle-Edwards 1985). When soil pH is between 7 and 8, nitrite accumulates whilst below pH 7 nitrate accumulates (Wetselaar *et al.* 1972). Therefore under the influence of irrigation it could be expected that nitrite would accumulate in soils that under rainfed

conditions contain little or no nitrite. At Kununurra, crops normally grown rainfed at Katherine, are produced with the aid of irrigation. As is the case at Katherine, this leads to an increase in soil pH. Chapman and Liebig (1952) found that no nitrite accumulated from a range of nitrogen sources in soils with pH below 6.0. However when soils at pH 7.0 were treated with the same range of nitrogen sources nitrite accumulated only in the urea treatment. The actual pH of the soil upon treatment with urea in their experiment rose from 7.0 prior to treatment to 8.2 one week following addition of urea. This illustrates the importance not only of soil pH in aggravating nitrite accumulation but also of the nitrogen source in creating conditions that favour accumulation. Concentrations as low as 10ppm nitrite have been reported to be toxic to roots (Bingham 1954). Court, Stephens and Waid (1962) described how the accumulation of nitrite in the firsts four weeks after treatment with urea caused marked phytotoxicity and reduction in plant yield. A growth lag of about 30 days with lettuce grown on alkaline soil treated with urea was associated with the duration of nitrite build-up, and normal growth resumed only when nitrites fell to low levels (Paul and Pollen 1965).

Evidence for a range of crops grown on alkaline soils indicates that nitrogen application (particularly urea) can lead to the accumulation of phytotoxic concentrations of nitrite that seriously reduce plant growth and crop yield. It would be reasonable to suggest on the basis of this evidence that nitrite accumulation may well be limiting production at Katherine.

If applied fertiliser remained near the surface where it was susceptible to drying then the nitrification could be disrupted. This phenomena was recognised by Wetselaar *et al.* (1960). With frequent irrigation soil water tension should not be a limiting factor in the formation of nitrate. It is possible that the benefits often observed when the time between irrigation events is decreased is not solely due to a reduced moisture stress on the plant, but partly to an increased amount of nitrate available for uptake.

CONCLUSION:

Watermelon yields vary enormously at Katherine both from one planting to the next and from season to season. Experimental planting at Coastal Plains Research Station near Darwin have shown a similar variability in yield. The crop monitored in this experiment was the most successful the farmer had ever grown.

It has been shown that an irrigated high value crop can be grown commercially on a Venn sandy loam without significant leaching. The following reasons may possibly have contributed in some part to the success of the crop:

- -irrigation was applied largely in response to crop water needs;
- -fertiliser application and nitrification contributed to peak extractions of nitrate between flowering and mid-fruit development;
- -nitrate was not leached below the depth of young growing plants;
- -nitrate did not accumulate at depth and become available for extraction late in the development of the crop;
- -large quantities of nitrogen were made available and were extracted by the crop.

The results and discussion above point to areas that warrant consideration by growers and further investigations by scientists. Such areas include:

-water requirements in relation to crop phenology;
-physiological responses to water stress;
-nitrogen release and immobilisation from incorporated crop residues;
-nitrification of applied fertiliser;
-nitrate leaching under different irrigation regimes;
-nitrite toxicity.

The development of a combined water, nitrogen and energy balance for this crop may be of particular commercial value. It is important to establish the criteria for producing high yielding high quality crops such as the one monitored here and to explain why the present variation in crop performance exists.

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REFERENCES:

Aldrick, J.M., and Robinson, C.S. (1972) Report on the land units of the Katherine-Douglas area, N.T. Conservation Commission on the N.T. Land Conservation Series No. 1.

Allison F.E. (1966) The fate of nitrogen applied to soil. Advances in Agronomy **18:** 219-258.

Angus J.F., Hasegawa S., Hsiao T.C., Liboon S.P. and Zandstra H.G. (1983) The water balance of post-monsoonal dryland crops. J. agric. Sci., Camb. **101:** 699-710.

Arndt W. and Norman M.J.T. (1959) Characteristics of native pasture on Tippera clay loam at Katherine NT. CSIRO Aust. Div. Land Res. Reg. Surv. Tech. Pap. No. 3.

Arndt W., Phillips, L.J. and Norman M.J.T. (1963) Comparative performance of crops on three soils of the Tipperary region, NT. CSIRO Aust. Div. Land Res. Reg. Surv. Tech. Pap. No. 23.

Arndt W. (1966) Traffic compaction of soil and tillage requirements. IV The effect of traffic compaction on a number of soil properties. J. Agric. Eng. Res. **11:** 182-187

Arndt W. and Rose C.W. (1966a) Traffic compaction of soil and tillage requirements. II A theory of the effect of variable traffic compaction on the overall relative magnitude of soil properties of a field. J. Agric. Eng. Res. **11:** 176-177.

Arndt W. and Rose C.W. (1966b) Traffic compaction of soil and tillage requirements. III A model of soil water storage for tillage studies. J. Agric. Eng. Res. **11:** 178-181.

Australian Bureau of Meteorology (1988) Climatic atlas of Australia. Aust. Gov. Pub. Serv. Canberra.

Begg J.E., Bierhuizen J.F., Lemon E.R., Misra D.K., Slatyer R.O. and W.R. Stern (1964) Diurnal energy and water exchanges in bulrush millet in an area of high solar radiation. Agr. Meteorol. **1** 294-312.

Begg, J.E., and Turner, N.C. (1976) Crop water deficits. Advances in Agronomy **28:** 161-217.

Blackburn, K., Ramsay, G., Jettner, and Traynor, M. (1989) Melon irrigation scheduling. N.T. Department Primary Industry and Fisheries Tech. Bull. 139.

Birgham, F.T., Chapman, H.D., and Pugh, A.L. (1954) Solution-culture studies of nitrite toxicity to plants. Soil Sci. Soc. Am. Proc. **18** 305-308.

Bristow, K.L., and Aorecht, D.G. (1989) The physical environment of two semi-arid tropical soils with partial surface mulch cover. Aust. J. Soil Res. **27** 577-87.

Broadbent, F.E. (1962) Biological and chemical aspects of mineralisation. Transactions of joint meeting of Commission 4 and 5, Int. Soc. Soil Sci. **220.**

Chalmers, D.J., Mitchell, P.D., and van Heek, L. (1981) Control of peach tree growth and productivity by regulated water supply, tree density and summer pruning. J. Am. Soc. Hortic. Sci. **100:** 307-312.

Chapman, H.D., and Liebig, G.F. (1952) Field and laboratory studies on nitrate accumulation in soils. Soil Sci. Soc. Am. Proc. **16:** 276-282.

Clements, H.F. (1964) Annu. Rev. Plant Physiol. **15:** 409-442. In Begg and Turner (1976). (original not cited).

Court, M.N., Stephen, R.C., and Waid, J.S. (1962) Nitrite toxicity arising from the use of urea as a fertiliser. Nature **194:** 1263-1265.

Day, K.J. (1977) Fertility studies on three red earth soils of the Daly Basin, Northern Territory. N.T. Department of Primary Industry and Fisheries Tech. Bull. No. 22.

Denmead, O.T., and Shaw, R.H. (1960) The effect of soil moisture stress at different stages of growth on the development and yield of corn. Agron. J. **52** 272-274.

Denmead, O.T., and Shaw, R.H. (1962) Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J. **54** 385-390.

Dyer, A.J. (1967) A combined water and energy balance study at Katherine N.T. Aust. Met. Mag. **15:** 148-155.

Eno, C.F. and Blue, W.G. (1957) The comparative rate of nitrification of anhydrous ammonia, urea and ammonium sulphate in sandy soils. Soil Sci. Soc. Am. Proc. **21:** 392-396.

Eno, C.F. and Blue, W.G. (1957) The effect of anhydrous ammonia on nitrification and microbiological populations in sandy soils. Soil Sci. Soc. Am. Proc. **18:** 178-181.

Gardiner, W.R. (1965) Dynamic aspects of soil-water availability to plants. A. Rev. Pl. Physiol. **16** 323-342.

Gates C.T. (1955_a) The response of the young tomato plant to a brief period of water shortage I. Whole plant and its principal parts. Aust. J. Biol. Sci. **8** 196-214.

Gates C.T. (1955_b) The response of the young tomato plant to a brief period of water shortage II. The individual leaf. Aust. J. Biol. Sci. **8** 215-230.

Gates, C.T. (1957) The response of the young tomato plant to a brief period of water shortage. III Drifts in nitrogen and phosphorus. Aust. J. Biol. Sci. **10** 125-146.

Gates, C.T. (1964) The effect of water stress on plant growth. J. Aust. Inst. Agric. Sci. **30** 3-22.

George, P.R., and Cripps, J.E.L. (1985) Water requirements of vegetables grown on sandy soils. Western Australian Department of Agriculture Farmnote No. 102/85.

Grierson, W., Soule, J., and Kawada, K. (1982) Beneficial aspects of physiological stress. Hortic. Rev., **4:** 247-271.

Jenkinson, D.S. (1966) Studies on the decomposition of plant material in soil. II Partial sterilisation of soil and the soil biomass. J. Soil Sci. **17:** (2) 280-302.

Jenkinson, D.S. (1971) Studies on the decomposition of C^{14} labelled organic matter in soil. J. Soil Sci. **3:** (1) 64-70.

Kalma, J.D. (1971) The annual course of air temperature and near-surface soil temperature in a tropical savannah environment. Agr. Meteorol. **8:** 293-303.

Kraus, C. (1991) Northern Territory primary production statistics 1989-90. N.T. Department Primary Industry and Fisheries Tech. Bull. (in press).

Kissell, D.E., Smith, S.J., and Dillow, D.W. (1976) Disposition of fertiliser nitrate applied to a swelling clay soil in the field. J. Environ. Qual. **5** 66-71.

Ladd, J.N., Parsons, J.W., and Amato M. (1977) Studies on nitrogen immobilisation in calcareous soils. II Mineralisation of immobiliser nitrogen from soil fractions of different particle size and density. Soil Biol. Biochem. **9:** 319-325.

Lucas, S.J., Day, K.J., and Wood B. (1985) Revised classification of the earth soils of the Daly Basin, N.T. Conservation Commission of the N.T. Tech. Memo. 85/8.

Luke, G.J., Burke, K.L., and O'Brien, T.M. (1988) Evaporation data for Western Australia. Western Australian Department of Agriculture Tech. Rep. 65.

Muchow, R.C. (1985) Phenology, seed yield and water use of grain legumes grown under different soil water regimes in a semi-arid tropical environment. Field Crops Res. **11:** 81-97.

Muchow, R.C. (1989) Comparative productivity of maize, sorghum and pearl millet in a semiarid tropical environment. II Effect of water deficits. Field Crops Res. **20:** 207-219.

Myers, R.J.K. and Paul, E.A. (1968) Nitrate ion electrode method for soil nitrate nitrogen determination. Can. J. Soil Sci. **48:** 369-371.

Myers, R.J.K. (1972) data obtained from CSIRO file NA1/29 K. 512.

Myers, R.J.K. (1978) Nitrogen and Phosphorus nutrition of dryland grain sorghum at Katherine, Northern Territory. III Effect of nitrogen carrier, time and placement. Aust. J. Exp. Agric. Anim. Hus. **18:** 834-843.

Myers, R.J.K. (1979) Nitrogen and phosphorus nutrition of dryland grain sorghum at Katherine, Northern Territory. IV 15-Nitrogen studies on nitrogen carrier and method of application. Aust. J. Exp. Agric. Anim. Husb. **19:**481-487.

Myers, R.J.K. (1983) The effect of plant residues on plant uptake and leaching of soil and fertiliser nitrogen in a tropical red earth soil. Fertiliser Res. **4:** 249-260.

Norman, M.J.T. (1966) Katherine Research Station 1956-64: A review of published work. CSIRO Aust. Div. Land Res. Tech. Pap. No. 28.

Norman, M.J.T., and Begg, J.E. (1973) Katherine Research Station: A review of published work, 1965-72. CSIRO Aust. Div. Land Res. Tech. Pap. No. 33.

Northcote, K.H. (1971) A factual key for the recognition of Australian soils. Rellim. South Aust., 3rd edn.

Paul, J.L., and Polle, E. (1965) Nitrite accumulation related to lettuce growth in a slightly alkaline soil. Soil Sci. **100:** 292-297.

Reddy, S.J. (1983) A simple method of estimating the soil water balance. Agric Meteor. **28:** 1-17.

Ritchie J.T. (1972) Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. **8:** 1204-1213.

Robinson, J.C., and Alberts, A.J. (1989) Seasonal variations in the crop water-use coefficient of banana (cv. Williams) in the subtropics. Scientia Hortic. **40:** 215-225.

Rose, C.W., and Stern, W.R. (1965) The drainage component of the water balance equation. Aust. J. Soil Res. **3:** 95-100.

Rose, C.W. (1968a) Water transport in soil with a daily temperature wave. I Theory and experiment. Aust. J. Soil Res. **6:** 31-44.

Rose, C.W. (1968b) Water transport in soil with a daily temperature wave II Analysis. Aust. J. Soil Res. **6:** 45-57.

Ross, P.J., Williams, J., and McCown, R.L. (1985) Soil temperature and the energy balance of vegetative mulch in the semi-arid tropics. II Dynamic analysis of the total energy balance. Aust. J. Soil Res. **23** 515-532.

Shibles, R., Anderson, I.C., and Gibson, A.H. (1975) Soybean. In Evans L.T. (ed.). Crop physiology some case histories. Cambridge University Press.

Sinclair, T.R., and Ludlow, M.M. (1986) Influence of soil water supply on the plant water balance of four tropical grain legumes. Aust. J. Plant Physiol. **13:** 329-341.

Sinclair, T.R., Muchow, R.C., Ludlow, M.M., Leach, G.J., Lawn, R.J., and Foale, M.A. (1987) Field and model analysis of the effect of water deficits on carbon and nitrogen accumulation by Soybean, Cowpea and Blackgram. Field Crops Res. **17:** 121-140.

Slatyer, R.O. (1954) Studies on the water relations of crop plants grown under natural rainfall in northern Australia. Aust. J. Agric. Res. **6:** 365-377.

Slatyer, R.O. (1956) Evapotranspiration in relation to soil moisture. Netherlands J. Agric. Sci. **4:** 73-76.

Slatyer, R.O. (1957) The influence of progressive increases in total soil moisture stress on transpiration, growth, and internal water relationships of plants. Aust. J. Biol. Sci. **10** 320-336.

Slatyer, R.O. (1960) Agricultural climatology of the Katherine area, N.T. CSIRO Aust. Div. Land Res. Reg. Surv. Tech. Pap. No. 13.

Slatyer, R.O. (1969) Physiological significance of internal water relations in crop yield. In Eastin, J.D., Haskins, F.A., Sullivan, C.Y., and Van Bavel, C.H.M. (ed.) Physiological aspects of crop yield. Am. Soc. Agron. Winsconsin.

Smith, C.J., and Chalk, P.M. (1980) Gaseous nitrogen evolution during nitrification of ammonia fertiliser and nitrite transformations in soils. Soil Sci. Soc. Am J. **44:** 277-282.

Stanford, G., Frere, M.H., and Vander Pol, R.A. (1975) Effect of fluctuating temperatures on soil nitrogen mineralisation. Soil Sci. **119:** 222-226.

Soil Survey Staff (1975) 'Soil taxonomy A basic system of soil classification for making and interpreting soil surveys.' U.S. Dept Agric., Handb. No. 436. (U.S. Govt Printing Office: Washington, D.C.)

Torssell, B.W.R. (1973) Microrelief and edaphic factors in lateritic red earths in dry monsoonal climate. CSIRO Aust. Div. Land Use Res. Tech. Pap. No. 73/5.

Wade, M.K. and Sanchez, P.A. (1983) Mulching and green manure applications for continuous crop production in the Amazon Basin. Agron. J. **75:** 39-45.

Wetselaar, R., and Norman, M.J.T. (1960) Soil and crop nitrogen at Katherine, N.T. CSIRO Aust. Div. Land Use Res. Reg. Surv. Tech. Pap. No. 10.

Wetselaar, R (1961a) Nitrate distribution in tropical soils. I Possible causes of nitrate accumulation near the surface after a long dry period. Pl. Soil **15:** 110-120.

Wetselaar, R. (1961b) Nitrate distribution in tropical soils. II Extent of capillary accumulation of nitrate during a long dry period. Pl. Soil **15:** 121-133.

Wetselaar, R. (1962a) Nitrate distribution in tropical soils. III Downward movement and accumulation of nitrate in the subsoil. Pl. Soil **16:** 19-31.

Wetselaar, R. (1962b) The fate of nitrogenous fertilisers in a monsoonal climate. Int. Soc. Soil Sci. Trans. Commiss. IV and V, New Zealand. 588-595.

Wetselaar, R. (1967) Determination of the mineralisation coefficient of soil organic nitrogen on two soils at Katherine, N.T. Aust. J. exp. Agric. An. Husb. **7:** 266-274.

Wetselaar, R. (1968) Soil organic nitrogen mineralisation as affected by low soil water potentials. Pl. Soil **29:** 9-17.

Wetselaar, R., Passioura, J.B., and Singh, B.R. (1972) Consequences of banding nitrogen fertilisers in soil. I Effects on nitrification. Pl. Soil **36:** 159-175.

Wetselaar, R., Jakobsen, P., and Chaplin, G.R. (1973) Nitrogen balance in crop systems in tropical Australia. Soil Biol. Biochem. **5:** 35-40.

Whitehouse, M.J., and Leslie, J.K. (1973) Movement, pH effect and nitrification of band-applied anhydrous ammonia, urea and sulphate of ammonia in an alkaline black earth. Qld. J. Agric. Anim. Sc. **30:** 301-310.

Wilcox, J.C. (1959) Rate of soil drainage following an irrigation. I Nature of soil drainage curves. Can. J. Soil Sci. **39:** 107-119.

Wilcox, J.C. (1960) Rate of soil drainage following an irrigation. II Effect on determination of rate of consumptive use. Can. J. Soil Sci. **40:** 15-27.

Wilcox, J.C. (1962) ibid **42** 122-128. In Gardner (1965). (original not cited).

Wright, G.C., and Catchpoole, V.R. (1985) Fate of urea nitrogen applied at planting to grain sorghum grown under sprinkler and furrow irrigation on a cracking clay soil. Aust. J. Agric. Res. **36:** 677-84.

Wright, G.C., Foale, M.A., and Charles-Edwards, D.A. (1985) Nitrogen nutrition of grain sorghum under sprinkler and furrow irrigation in the tropical dry season. I Plant establishment, nitrogen uptake and grain yield. Field Crop Res. **12** 203-222.