A new method for benchmarking salt and nitrate leaching

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SUMMARY

Before this study, CSIRO Land & Water developed an irrigation scheduling tool called the FullStop™. The device is buried in the soil and tells a farmer when a wetting front has reached the required depth in the soil and therefore when to stop irrigating. The device also collects and stores a sample from the wetting front that can be used to measure the concentration of solutes that are moving in the soil.

This study describes a one-year pilot project to determine if the water sample from the FullStop could be used to manage nitrate and salt in irrigated agriculture. The emphasis was on looking at the simplicity, robustness and potential usefulness to farmers. We examined the performance of the FullStop in several different crops and soil types under both drip and sprinkler irrigation. Case studies are presented from sugarcane in Bundaberg, capsicums in Gosford and tomatoes and turf in Canberra.

The FullStop responded to wetting fronts generated by irrigation and rainfall at all sites and almost always stored a soil solution for analysis. At Bundaberg the major leaching events were forced by rainfall, and since these events are not predictable it is important to keep nitrate levels as low as practicable. The high N levels recorded after fertigation at 0.5 m suggests to the manager that fertiliser application would be better in smaller, probably more frequent doses. Results from Gosford and Canberra showed how easily nitrate is lost from the topsoil early in the season. In both cases there was evidence that the plants receiving less water early in the season performed best because nitrate leaching was reduced.

The FullStop method highlighted the critical interaction between water and fertiliser management and provided useful feedback to the manager. This study concludes that the FullStop can be used to save water and improve the management of nitrate and salt in irrigated agriculture.

A NEW METHOD FOR BENCHMARKING SALT AND NITRATE LEACHING

Introduction

CSIRO Land & Water has developed a new irrigation scheduling tool called the FullStop^{TM}. The device is a wetting front detector that is buried in the root zone. During an irrigation event a wetting front is produced which moves into the root zone. The FullStop tells the irrigator when the wetting front has reached the required depth in the soil (i.e. when the soil is full - stop irrigation).

If the soil is relatively dry before irrigation the wetting front moves slowly into the root zone. This occurs because the soil absorbs much of the water and hence slows the progress of the front into the soil. In this case a long irrigation is permitted before the wetting front reaches the FullStop. Conversely, if the soil is already wet, the wetting front moves fast and the irrigation event is quickly terminated. Thus the device determines the duration of irrigation based on the initial water content of the soil.

The FullStop is a funnel shaped container that converges the unsaturated flow lines to a small area at its base. When a wetting front is at the depth of the FullStop, the moisture at the base of the funnel is increased to the point of saturation. Free water flows through a porous filter into a chamber where it is detected by an electrical float switch. As the soil surrounding the FullStop dries out, the water is withdrawn from the cavity by capillary action and the FullStop is "reset" for the next irrigation (see Figure 1).

In summary, the FullStop produces a liquid sample of water from an unsaturated soil. The purpose of this project was to find out whether we could use this water sample to help schedule nitrogen fertiliser applications and monitor the accumulation of salt in the root zone. We needed to:

1. Redesign the FullStop so that water produced by convergence at the base of the funnel could be stored in the device
2. Determine the amount of water stored in a typical irrigation event
3. Analyse the samples for salt and nitrate and compare with conventional measurement methods (suction cups)
4. Evaluate the role of the FullStop as a salt/nitrate monitoring device for farmers.

This was a one-year pilot study to examine the feasibility of the approach. The emphasis was on looking at the simplicity, robustness and potential usefulness of the method to farmers. Thus we chose to take a broad overview by examining the method on several different crops and soil types under both drip and sprinkler irrigation.

The problem

Salt and nitrate levels can fluctuate rapidly during the growing season, making routine monitoring very difficult. Moreover it is difficult to manage a mobile element in the soil (NaCl, NO_3^-) without knowing how deep the water that carries it is penetrating with respect to the depth of the root zone. To manage salt and nitrate we must combine knowledge of the position of the wetting front and the concentration of solutes moving in it. Herein lies the strength of the FullStop system.

The inefficiency of nitrogen use in Australian irrigated agriculture is clearly evident when comparing the rates of fertiliser recommended by State agencies and the removal of N in the harvested portion of the crop. Even if farmers limited themselves to recommended fertiliser rates, and obtained target yields, the efficiency of N use would be 30 to 50% for most fruit and vegetable crops (Stirzaker 1999). Experimental evidence suggests the efficiencies are even lower. Trials reproducing "district farmer practice" conducted by the NSW Agriculture at Gosford show an estimated 633 kg N ha^{-1} was leached in an 18 months period during which capsicum and cabbage crops were grown, giving an overall crop nitrogen use efficiency of 13%. Recoveries were improved to 51% under conditions of "best management practice" (Dougherty and Wells 1998). Low recoveries for vegetable crops have been found in other countries; Greenwood et al. (1974) present N:P:K recoveries of 7%, 2% and 8% for lettuce and 65%,6% and 55% for potatoes under UK conditions. McNab *et al*. (1994) recovered 44-70 kg N ha^{-1} y^{-1} from tile drains beneath an orchard in the Shepparton region and Gerritse *et al.* (1994) found that 20 to 50% of nitrate applied to orchards was lost in stream flow.

Periodic leaching of salt from the root zone is also essential for irrigated agriculture. The rate of watertable rise in slow-discharge catchments demonstrates that long term leaching over the catchment as a whole is excessive. Yet it is highly likely that transient build up of salt at critical times causes reduced fruit size and sometimes tree death (Boland *et al* 1998). It is therefore essential to monitor the salt accumulation in the root zone but at the same time keep the leaching fraction to a minimum.

Soil solution samplers

There is considerable literature on types of soil solution samplers together with their advantages and disadvantages. These issues have been well documented in review articles and will not be reproduced here in detail (e.g. Litaor 1988, Paramasivam *et al* 1997). For our purposes there are two types of soil solution samples for routine field use:

1. suction samplers, which exert a suction on the soil and draw solution through a filter
2. passive samplers, which require no external suction, but collect water because their shape distorts the flow path of water through the soil and produces saturation. Some passive samplers include wicks to increase the suction.

Suction samplers are most frequently used devices for research purposes. The FullStop is an example of a passive sampler.

Suction samplers

There are four principle factors that affect composition of solute collected from suction samplers:

1. The amount of suction applied to cup: Soil is held with increasing tension as pore size decreases. Since it is likely that the nutrient concentrations are related to pore size (more mobile water in larger pores will not be in equilibrium with the

resident water), higher suctions generally result in a higher concentration of nutrients. The reverse is often true following fertiliser application.

2. Length of time suction is applied to the cup: the first water drawn into the ceramic cups comes from the larger pores where the water is more mobile. Thus short duration suction volumes tend to be dominated by larger pores with the concentration changing with the length of time suction is applied. Seversen and Grigal (1976) found that concentrations of Ca^{2+} and K^+ increased with extraction time and PO_4^{3-} decreased.
3. The porous material used for the cup: cups are generally made of ceramic but may also be made from fritted glass, polyethylene, or increasingly, teflon. Ceramic is cheap and strong but recoveries of ions with a high charge density (NH_4^+, PO_4^{3-}) are often low because of sorption on high specific area material (Zimmermann et al 1978, Hansen and Harris 1975). The problem is avoided by using teflon, but its use is limited by the high cost and low air entry pressure. Fritted glass does not change the composition of the solution but it is fragile (Long 1978).
4. The size of the cup: Silkworth and Grigal (1981) showed that larger cups resulted in less variability than smaller cups. Larger cups had lower failure rates due to blocking or poor contact and produced greater sample volumes.

In summary, the initial soil water content, amount of suction applied to the cup, length of time suction is applied, spatial uniformity of the soil nutrients, composition and size of the cup combine to determine the concentration of ion collected by a suction sampler.

Passive samplers

Passive samplers are usually mini-lysimeters that collect water from the soil without the application of an external suction. Although they have been used for several decades their mode of operation remains poorly understood. Passive samples come in various shapes and sizes and often include suspended wicks to increase the passive suction (eg. Brandi-Dohrn *et al* 1996).

The greatest difficulty with passive samplers has been uncertainty over the conditions under which they collect a sample, particularly whether they collect a sample from the soil matrix or just intercept macropore flow. The issue has largely been resolved through research into the FullStop wetting front detector. This work has shown how to relate the size and shape of the mini-lysimeter to the suction at which it will collect water from an unsaturated soil (Hutchinson and Stirzaker in prep). The FullStop has been designed to collect water at a suction of around 2 kPa. Our experience is that wetting fronts move at suctions wetter than 2 kPa in all soil when water is applied at a rate within the range of commercially available irrigation equipment. Thus the FullStop will collect a solution sample whenever a wetting front produced by irrigation passes.

The mode of operation of the passive sampler means that it collects water in a reproducible way that would be expected to minimise some of the variability common with suction samplers (Barbee and Brown 1986). The fact that passive samplers only collect when the soil is very wet means that they are sampling mobile as opposed to resident concentrations. The passive samplers are therefore more suited to measuring what is leaving the root zone, than the concentration of nutrients that may be available to plants (Magid and Christensen 1993, Simmons and Baker 1993). A second major difference between the two methods is that a suction cup only records a measurement when the operator is present to apply the suction (unless the system is highly automated and coupled with water measurement equipment). The erratic rain events that dominate solute movement are unlikely to be captured in this way. Correctly designed passive samplers will collect a sample whenever the soil reaches a known suction.

Modification of the FullStop

The cavity housing the float switch requires an air vent to allow air to escape into the outer shell of the FullStop as the water enters the cell through the filter (Figure 1). The air vent was modified to double as an overflow for soil solution. When the cell is filled, the excess flows through the overflow and collects in a storage reservoir at the base of the FullStop.

Overflow commences after about 20 mL of water has accumulated in and around the cavity. The storage reservoir holds 200 mL. When this storage volume is exceeded the excess water overflows the reservoir and drains back into the soil.

A tube connects the storage volume to the surface and samples can be removed with a syringe. Note that the float switch can trip without a water sample being collected (i.e.< 20 mL of water produced by convergence). However the storage of solution does not prevent the FullStop from resetting (i.e. the float returning to rest position). In some experiments described below the storage reservoir was emptied each day. In others it was emptied monthly, so that the solution represented a composite of several wetting fronts, although dominated by the latter events if overflow occurred.

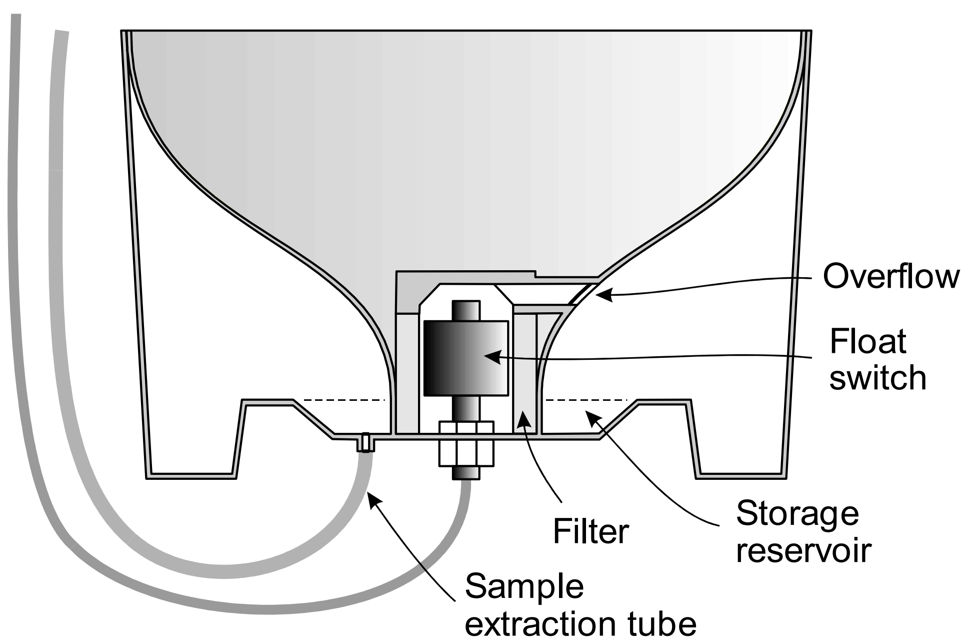


Figure 1. The modified FullStop with the ability to store a sample of soil solution produced by convergence in the funnel.

Experiments

The FullStops were redesigned and tested and 26 new devices were built with the capacity to store soil solution. Four experiments were carried between September 1998 and July 1999 as documented in Table 1.

Table 1. Summary of trial sites for the pilot experiments.

Location	Crop	Soil texture	Irrigation	FullStops	Collaborators
Bundaberg	Sugar	Clay Loam	Drip (buried)	6	CSIRO TAG
Gosford	Capsicum	Loamy Sand	Drip (surface) Sprinkler	8	NSW Dept. Ag.
Canberra	Turf	Sandy loam	Sprinkler	6	-
Canberra	Tomatoes	Sandy Loam	Drip (surface)	6	-

Bundaberg: Nitrate leaching in sugarcane

Aim To use the FullStop to record the times of rapid drainage from the root zone and the concentration of soluble nitrogen in the leachate.
To evaluate how times of drainage and N content of leachate relate to irrigation and fertiliser management.

Setup
Modified FullStops were installed at the Fairymead mill site, Bundaberg, on 13-14 October 1998. The cane, which had just been cut, was planted on low ridges in rows 1.5 m apart. Netafim tape (spacing between emitters 0.6 m, emitter discharge 1.65 L/h) was buried 0.27 m below the surface of the ridge. Six detectors were installed, two in each of three nitrogen treatments (0, 80 and 240 kg N ha^{-1}) at depths of 0.5 and 1 m below the soil surface.

Bundaberg was the only site where installation was made into relatively undisturbed soil. Three trenches, 0.7 m wide and 1.2 m deep, were excavated in the interrow region, leaving 0.4 m of undisturbed soil to centre of cane row. Fullstops were installed by digging a hole laterally through the undisturbed soil at the relevant depth. The upper detector (0.5 m depth) was placed 0.23 m directly below an emitter. The need to verify the location of a buried emitter meant that there was some soil disturbance above the detector. The lower detectors (1 m) were installed with no disturbance to the soil profile above.

The experiment was carried out in conjunction with CSIRO Tropical Agriculture (TAG) who had conventional soil solution suction equipment installed at the same depths as the FullStops. TAG made monthly visits to the site and extracted soil solution from FullStops and suction samplers. The six FullStops were connected to mini loggers that recorded every time the float rose and fell.

Results
The FullStops were placed at 0.5 m because the irrigation managers considered that the majority of roots were above this depth, and at 1 m because water and N moving past this depth was likely to be beyond the root zone. For the purposes of this discussion we consider that a FullStop trip (float up) at 0.5 m represents an adequate irrigation, and a trip at 1 m represents leaching.

Figure 2a gives an overall picture of when wetting fronts reached 0.5 m and 1 m due to rain or irrigation over the duration of the experiment. The upper set of horizontal green, blue and red lines denote the time periods when the FullStops were tripped at a depth of 0.5 m and the lower set at a depth of 1 m (line starts when float rises and stops when float falls). The FullStops trip at a minimum suction of approximately 2 kPa. Thus we cannot say that leaching is confined to the periods when the FullStops are tripped, since drainage would occur in drier soil than this. However the FullStop output clearly shows when a sharp wetting front, initiated by rain or irrigation leaves the root zone.

The water balance was dominated by rainfall, not irrigation. There were eight periods from October to March when wetting fronts passed through 1 m, each coincident with peaks in the rainfall. Heavy rain in May also activated the deep FullStops. Irrigation regularly activated shallow FullStops but never the deep ones.

Figures 2b and 2c show the same data with time now plotted against soluble N ($N0_3^-$ + NH_4^+) at 0.5 and 1 m on the y-axis (note: the data in Fig 2c close to zero on the y-axis should be zero – treatments were offset slightly so that they did not superimpose). Fertiliser was applied as urea through the drip lines in 4 equal split dressings on 10/12/98, 31/12/98, 17/2/99 and 11/3/99. The N peak was observed to be higher and earlier in the 160 kg N ha^{-1} treatment compared to the 240 kg N ha^{-1} treatment. No N was detected past 1 m except a short period in the 240 kg N ha^{-1} treatment on 11 May when 109 mg l^{-1} was measured after heavy rain.

No N recovery at 1 m does not equate with no nitrate loss from the paddock through leaching. The FullStops only collect solution when the soil is 2 kPa or wetter. Drainage at drier suctions would occur, and would be likely to contain more N. This version of the FullStop is principally a management tool not a pollution monitoring device. The high N levels recorded at 0.5 m suggests to the manager that the fertigation would have been better in more frequent but smaller doses.

Water was contained in the storage reservoirs of the 0.5 m FullStops on 22 out of a possible 24 sampling events. On the two occasions when no water was stored, trips had been recorded. We suspect that the storage facility leaked as opposed to no overflow from the cell, since slow leakage was observed from other detectors from a faulty seal at the base of the reservoir. Soil solution samples were collected from the 1 m detectors 15 times. The occasions when no solution was collected always coincided with periods when there were no trips (i.e. no wetting front reached 1 m). In contrast, solution was only collected on 4 of the 24 sampling events from suction cups at 0.5 m and 5 of the 24 sampling events at 1 m.

The poor recovery from suction samplers makes comparison between the two methods difficult. Some comparison can be made between May and July, 2 to 3 months after the last fertiliser applications (Table 2). The suction cups recorded high soluble N during this period when the FullStops collected low N in the moving water. This highlights how the two methods sample different parts of the soil solution.

Conclusions

1. Water balance was dominated by rainfall not irrigation
2. Irrigation was not carried out to excess
3. High N concentrations were captured at 50 cm but almost none at 1 m except for one short event in May 1999 following rainfall
4. Low N recovery at 1 m does not equate to low nitrate loss from the paddock through leaching. Drainage at drier suctions would occur and may contain a high concentration of N.

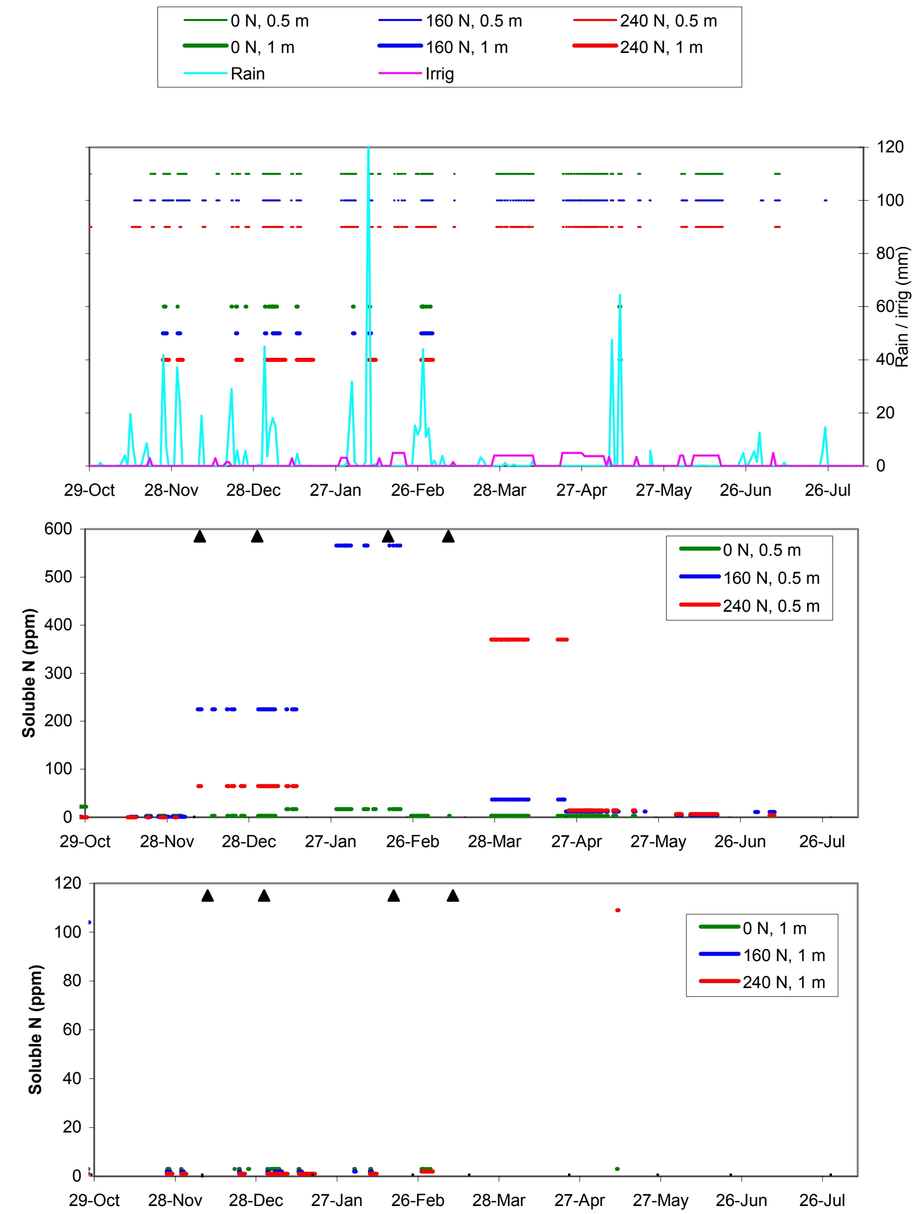


Figure 2 a) Period when FullStops were tripped at 0.5 m (upper set of horizontal lines) and 1 m (lower set) together with rain and irrigation.
b) The soluble N concentration at 0.5 m. Black triangles mark fertigation times
c) The soluble N concentration at 1 m. Black triangles mark fertigation times

Table 2. Soil solution was removed from the FullStops eight times and the rainfall, irrigation (number of irrigations in parenthesis) and Et for each period as shown below. The number of times the FullStops tripped, the proportion of time that the detectors remained in the tripped state and soluble N in the stored water and soluble N from suction cups at the same depth are recorded. (Suction cup data from Thorburn and Smith)

Period	N rate (kg ha^{-1})	Depth (m)	Trip number	Trip time (% of total)	FullStop N (mg l^{-1})	Suction N (mg l^{-1})
1. 29 Oct to 8 Dec 98	240	0.5	4	20	0	1
(40 days)	160	0.5	4	32	0	-
	0	0.5	4	33	0	-
Rain 157 mm	240	1	2	10	0	0
Et 217 mm	160	1	4	6	0	0
Irrig 0 mm	0	1	3	1	0	-
2. 8 Dec to 18 Jan 99	240	0.5	7	34	65	20
(41 days)	160	0.5	7	30	225	-
Rain 176 mm	0	0.5	6	26	0	-
Et 211 mm	240	1	3	38	0	9
Irrig 11 mm	160	1	4	12	0	53
(5)	0	1	8	10	0	-
3. 18 Jan to 24 Feb 99	240	0.5	15	29	-	-
	160	0.5	10	15	566	-
(37 days)	0	0.5	13	29	0	-
Rain 181 mm	240	1	1	7	0	-
Et 199 mm	160	1	2	3	0	-
Irrig 30 mm (8)	0	1	2	2	0	-
4. 24 Feb to 17 Mar 99	240	0.5	4	36	-	-
	160	0.5	2	21	1296	-
(21 days)	0	0.5	4	26	17	-
Rain 118 mm	240	1	1	20	1	-
Et 90 mm	160	1	3	15	0	-
Irrig 2 mm (1)	0	1	4	7	0	-
5. 17 Mar to 23 Apr 99	240	0.5	14	29	370*	-
	160	0.5	16	16	37*	-
(37 days)	0	0.5	19	27	0	-
Rain 10 mm	240	1	0	0	-	-
Et 136 mm	160	1	0	0	-	-
Irrig 81 mm (19)	0	1	0	0	-	-

* Lab samples lost: N measured by nitrate test strips

Period	Site	Depth	Trip number	Trip time (% of total)	FullStop N (mg l^{-1})	Suction N (mg l^{-1})
6. 23 Apr to 26 May 99	240	0.5	15	37	14	-
(40 days)	160	0.5	16	39	12	-
Rain 6 mm	0	0.5	16	27	0	-
Et 37 mm	240	1	1	1	109	-
Irrig 84 mm (22)	160	1	0	0	-	-
	0	1	1	1	0	-
7. 26 May to 22 Jun 99	240	0.5	10	36	7	155
(28 days)	160	0.5	9	38	4	-
Rain 1 mm	0	0.5	12	29	0	-
Et 78 mm	240	1	0	0	-	-
Irrig 36 mm (12)	160	1	0	0	-	-
	0	1	0	0	6	-
8. 22 Jun to 29 Jul 99	240	0.5	1	5	4	123
(37 days)	160	0.5	2	8	11	-
Rain 52 mm	0	0.5	2	5	0	-
Et 90 mm	240	1	0	0	-	233
Irrig 3 mm (1)	160	1	0	0	-	-
	0	1	0	0	-	-

Note: The irrigation record was incomplete. The irrigation strategy was to apply the same amount of water on consecutive days until the next rainfall. FullStop data clearly showed that there were days when irrigation had been applied but the irrigation data not recorded. These missing days were assumed to have received the same irrigation as the previous day.

Gosford: Nitrate leaching under capsicum

Aim To compare the times of rapid drainage as measured by FullStop and TDR
To measure the nitrate composition of the leachate and to evaluate how times of drainage and N content of leachate relate to irrigation and fertiliser management

Setup

Modified FullStops were installed on 22 and 23 December 1998 into long-term vegetable trials at the Somersby site of NSW Agriculture. The experiment compared the water and nutrient use efficiency and productivity of irrigated vegetables under district practice, departmental recommendations, organic and low input management regimes. The soil was comprised of 25-30 cm of loamy sand overlying a sandy clay containing gravel and rocks. The current crop in the rotation was capsicum, planted in double rows 0.6 m apart, 0.5 m apart in the row, on raised beds at 1.7 m spacing. The crop was transplanted on 12 January and harvesting was completed by early June. Two treatments were chosen for the installation of FullStops having contrasting irrigation systems, - "district practice" under sprinkler and "departmental recommendation" under drip irrigation.

There was one line of surface drip tape per raised bed with 1.7 l h^{-1} emitters spaced 0.6 m apart. Two FullStops were buried at 30 cm and two at 70 cm in each irrigation treatment. The upper FullStops controlled irrigation and the lower FullStops collected leachate leaving the root zone. Conventional soil solution suction cups were also installed adjacent to the 70 cm FullStops. TDR probes were positioned around the FullStops and logged every 10 minutes to check whether the FullStops detected each wetting front.

The sprinkler treatment had a similar installation of four FullStops, TDR and soil solution suckers except that the upper FullStops were located at 20 cm, since the wetting front must be intercepted earlier in sprinkler compared to drip irrigation. This is because the wetted soil from a dripper is redistributed in three dimensions by the surrounding drier soil. In contrast, the wetting front from a sprinkler redistributes only downwards under gravity after the FullStop terminated irrigation. Irrigation was scheduled to this treatment by the Department of Agriculture without reference to FullStop output.

N fertiliser was applied to the drip treatment (total of 174 kg N ha^{-1}) in a split dressing on 28 January (87 kg N ha^{-1}) and 16 March (87 kg N ha^{-1}). N fertiliser was applied to the sprinkler treatment (total of 126 kg N ha^{-1}I) on 15 Dec 1998 (37 kg N ha^{-1} pre-plant) and on 2 Feb (45 kg N ha^{-1}) and 16 Mar (44 kg N ha^{-1}). The storage reservoirs were emptied on four occasions and nitrate concentration measured by the NSW Department of Agriculture using a colourmetric method.

Results

Figure 3 shows the time the FullStops tripped, the water content measured by TDR at the level of the float switch, and the rain plus irrigation for the drip irrigated treatment. The water balance was dominated by several large rainfall events. TDR measurements showed water reaching 70 cm coincident with rainfall peaks, and the 70 cm deep FullStops recorded each of these events (except for 31 March to 4 April when the FullStop data was lost due to a power failure). The TDR trace confirms that the FullStops always identify the periods of rapid leaching, even when these events appears as minor perturbations to the soil water content trace (Figure 3a, 70 cm).

Data for the sprinkler treatment are shown in Figure 4. We observed more variability between the two sites in response to the six irrigation events. At site 1, five of the six irrigation events activated the 70 cm detectors, compared to two out of six at site 2.

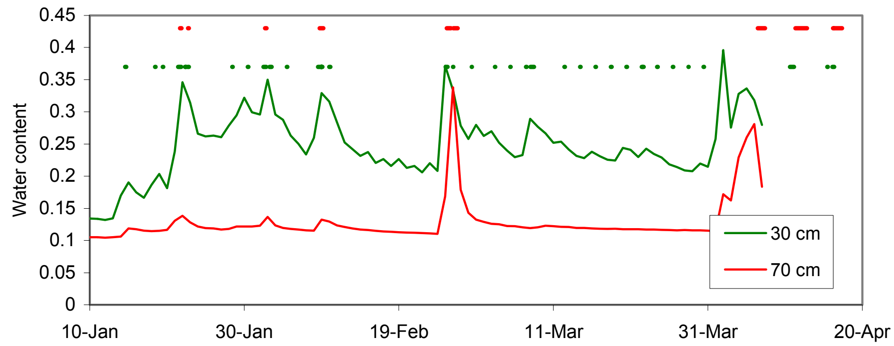
Nitrate concentrations fluctuated widely over the four sampling dates, sometimes with large difference between sites (e.g. drip, 30 cm). In general nitrate concentrations were higher in the sprinkler treatment despite the lower application rate. This may be due to the different N formulations given to the two treatments. A comparison between passive samplers and suction samplers was again difficult because the different methods did not always collect samples over the same time intervals.

Table 3. Nitrate concentration (mg l^{-1}) in storage reservoirs at four times during the experiment. Suction cup data was available from the 70 cm depths (- denotes no water sample).

Irrigation	Depth (cm)	Days from Planting	FullStop Site 1	Suction Site 1	FullStop Site 2	Suction Site 2
Drip	30	16	2		79	
	30	31	3		63	
	30	41	8		-	
	30	134	1		2	
	70	16	90	-	88	-
	70	31	21	23	36	-
	70	41	-	40	-	230
	70	134	-	30	-	-
Sprinkler	30	16	158		95	
	30	31	41		37	
	30	41	-		30	
	30	134	50		8	
	70	16	212	95	217	-
	70	31	61	37	53	51
	70	41	-	30	-	-
	70	134	-	8	-	-

Irrigation in the drip treatment was scheduled to start daily until the end of January, every two days until the end of March and every four days until the end of May. The irrigation was automatically switched on at 10:00 on the day of irrigation and terminated when one of the two FullStops at 0.3 m detected the wetting front. If rainfall activated a detector between irrigations, then the next irrigation was postponed until the prescribed interval had elapsed. Irrigation as scheduled by FullStops totalled 144 mm in forty nine events. This was the same (coincidentally) as the amount of water applied in the sprinkler treatment by NSW Agriculture (145 mm in six events). Total rainfall between planting and 20 May was 726 mm.

a)



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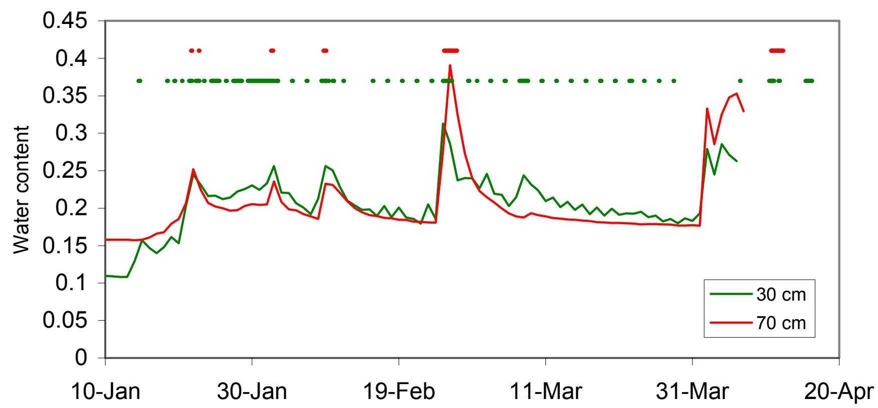

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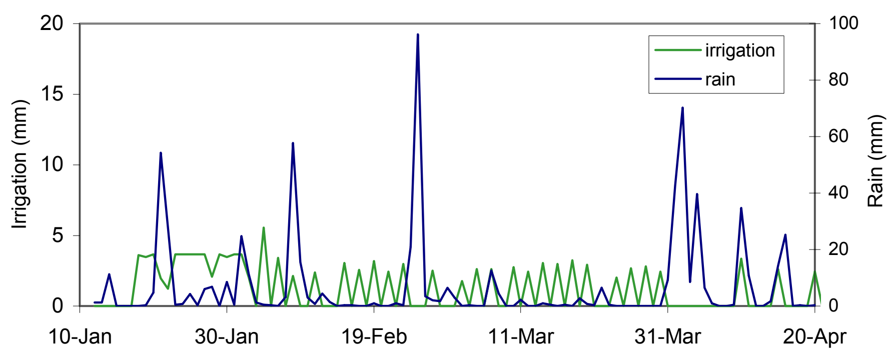


Figure 3 a) TDR traces and times when Fullstops were activated in drip treatment (rep1)
b) TDR traces and times when Fullstops were activated in drip treatment (rep2)
c) Daily irrigation and rainfall

a)

b)

c)

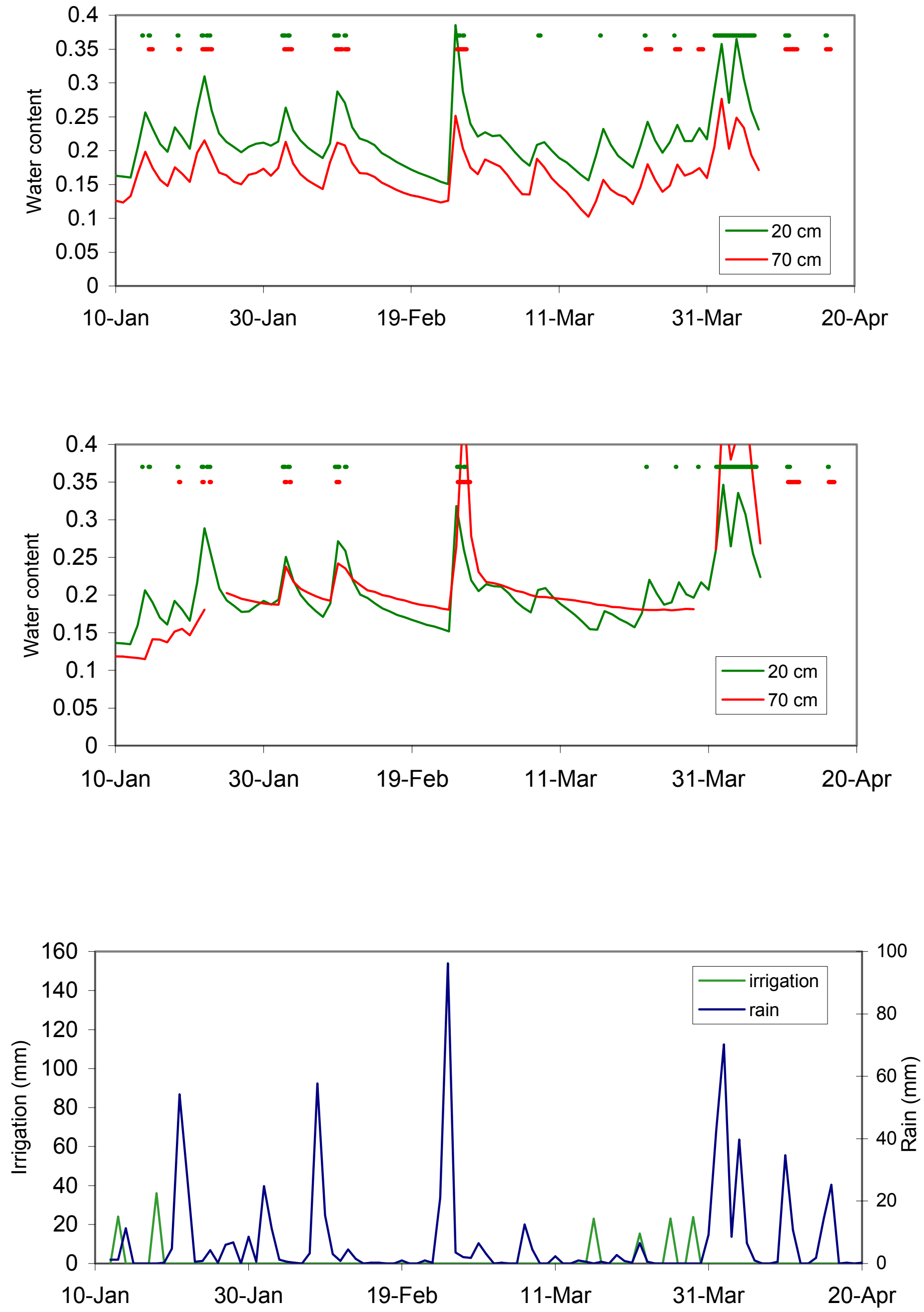


Figure 4 a) TDR traces and times when Fullstops were activated in sprinkler treatment (rep1)
b) TDR traces and times when Fullstops were activated in sprinkler treatment (rep2)
c) Daily irrigation and rainfall

Although this was not a replicated field trial, the growth (LAI and total DW) and yield of the drip treatment were lower than the sprinkler treatment. TDR traces show that the soil water status was more favourable in the drip treatment. However we speculate that the sprinkler treatment had access to more nitrogen. The sprinkler treatment received less irrigation before 15 March and appeared to use water from deeper in the soil (Figure 4a), where there was more available N. The example illustrates that good yields require both knowledge of the water status and soil water composition.

Table 4. Rainfall, irrigation, Leaf area index (LAI), total above ground dry weight (DW) and fruit fresh weight (FW) of the capsicum crop.

Treatment	Rain (mm)	Irrigation (mm)	LAI (28 Mar)	Total DW Kg ha^{-1}	Fruit FW kg ha^{-1}
Drip	726	144	0.41	1095	6176
Sprinkler	726	145	0.88	1707	8839

Conclusion

1. TDR record confirmed that FullStops recorded periods of rapid leaching
2. Growth differences highlight the interaction between irrigation management and nitrogen availability to the crop. The drip treatment with the more favourable average water content grew more slowly. The most likely reason is that the predominant location of water uptake (topsoil) differed from the predominant location of nitrate accumulation (subsoil).

Canberra: Nitrate leaching in tomatoes

Aim To measure the daily volume, nitrate composition and salinity of leachate from drip irrigated tomatoes
To evaluate the lowest cost method for routine measurement of nitrate on-farm

Setup
This experiment was run locally and therefore enabled daily measurement of solute volume collected by the FullStops, solute conductivity and mineral-N concentration. Tomatoes were planted in three rows into a sandy loam soil. Each row contained two FullStops, one at 20 cm and the other at 50 cm. The detectors were installed by augering a hole from the surface, since the soil had already been disturbed by cultivation. One line of Netafim drip tape (emitter spacing 0.3 m, discharge 2.3 L h^{-1}) was placed on the surface of each bed and tomato seedlings transplanted adjacent to each dripper on 11 December 1998.

Each row was independently irrigated. Water was turned on at a set time every day and off when the wetting front reached the 20 cm detector. If the wetting front detector did not trip, irrigation was stopped after an application of 13 mm. Thus the shallow detector was used to control irrigation and the deep detector used to monitor N leaving the profile (0.5 m taken as nominal depth of the active rootzone).

Tomatoes were given 10 kg N ha^{-1} weekly for seven consecutive weeks starting on 16 December. The fertiliser was dissolved in tap water and applied to the surface from a watering can. Each day the amount of irrigation supplied was recorded together with the volume of water in the overflow reservoir. Conductivity was measured with a Horiba B-173 portable "one drop" salinity meter and nitrate measured by nitrate test strips and segmented flow analyser (Alpkem 1992).

Results
If soil properties and crop growth were uniform, each row would have demanded the same amount of water. In practice row 2 required less water for most of January as there was a slight depression in the soil surface above the dripper and water collected above the FullStop from two emitters (hence the detectors tripped sooner). Smoothing of the soil surface in early February resulted in water running off the bed leading to over-irrigation (Figure 5a, Table 1). These effects were reflected in canopy growth (Figure 6b) and confirmed our previous experience that scheduling cannot be carried out successfully from just one detector, particularly under drip irrigation.

Table 5. Rainfall, irrigation fresh weight (FW) yield and water use efficiency (WUE) of the tomato crop.

	Rain (mm)	Irrigation (mm)	Total (mm)	FW Yield (kg m^{-2})	WUE g m^{-2} mm^{-1}
Row 1	99	277	376	10.03	27
Row 2	99	434	533	6.23	12
Row 3	99	351	450	6.67	15

Small differences in water application during the beginning of the season had a large impact on N leaching and yield. Figure 5b shows that the deeper detectors in rows 2 and 3 were continuously activated for four to six weeks after planting (lower detectors were not used for scheduling). Even though irrigation was stopped when the wetting front reached 20 cm, redistribution continued to move water past the root zone. This is a well known feature of the wetting front detector method. By definition the water content behind a wetting front is greater than the upper drained limit. It is essential that the plants withdraw some water below the detector to create a buffer for subsequent redistribution. This was of course not possible with young seedlings and thus the early irrigation scheduling was inappropriate.

The movement of wetting fronts below the root zone in rows 2 and 3 carried high concentrations of N (Figure 5d). This is in contrast to row 1 when high concentrations were observed at 20 cm, but not detected at 50 cm for several weeks after planting (and this was forced by a rain event). After 31 December almost no mineral N was recovered at 20 cm despite five applications of 10 kg N ha^{-1}. Leaching of nitrate beyond the nominal root zone had ceased by early January.

This was not a replicated trial, but the yield and water use efficiency appear to have been greatly influenced by the irrigation strategy during the first month when the plants were small (Figure 6b). The row receiving the least water produced substantially higher yield and achieved double the water use efficiency (Table 5).

The requirement for a rapid field assesment is important for farmers because the value in the FullStop method is to have immediate feedback on management actions so that subsequent decisions are optimised. Laboratory tests may have a turn around time of over a week and cost in excess of $20 per sample. Nitrate test strips require only one drop of solution and give an immediate reading for $0.60. Conductivity measurements are equally quick and even cheaper, provided we have some confidence in how to interpret the output, since it gives a measure of all ions in solution.

Figure 6a combines the nitrate data as measured by auto analyser and nitrate test strips together with the conductivity of the solution. Clearly the nitrate test strips provide sufficient accuracy for the purposes of fertiliser management. Figure 6c shows an acceptable correlation between conductivity and nitrate concentration at this site and management regime. It is likely that conductivity readings in excess of 0.5 dS m^{-1} in the leachate point to excess nitrate in the soil.

Figure 6d gives an example of the volume of solution retrieved each day from the detectors in one of the rows. In general the deeper FullStops collected more water than the shallower ones and the volume collected decreases as the plant's demand for water increases. The overflows almost always gave sufficient volumes of solution for analysis, and it was rare for a wetting front to be detected without obtaining a sample in the storage reservoir.

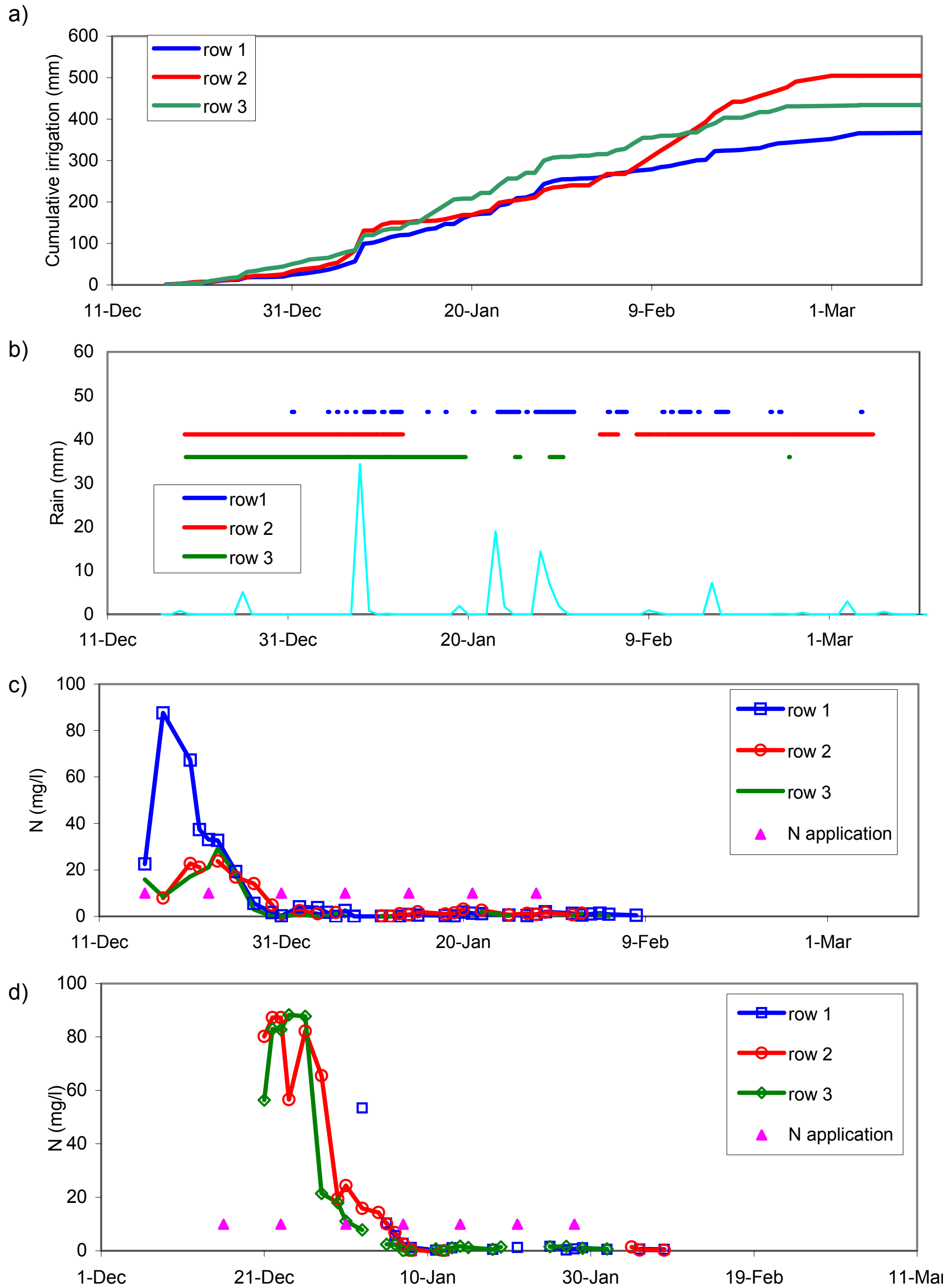


Figure 5 a) Cumulative rain plus irrigation to each row
b) Time period 50 cm (deep) FullStops tripped and daily rainfall
c) Mineral-N concentration (mg/l) in FullStops at 20 cm
d) Mineral-N concentration (mg/l) in FullStops at 50 cm

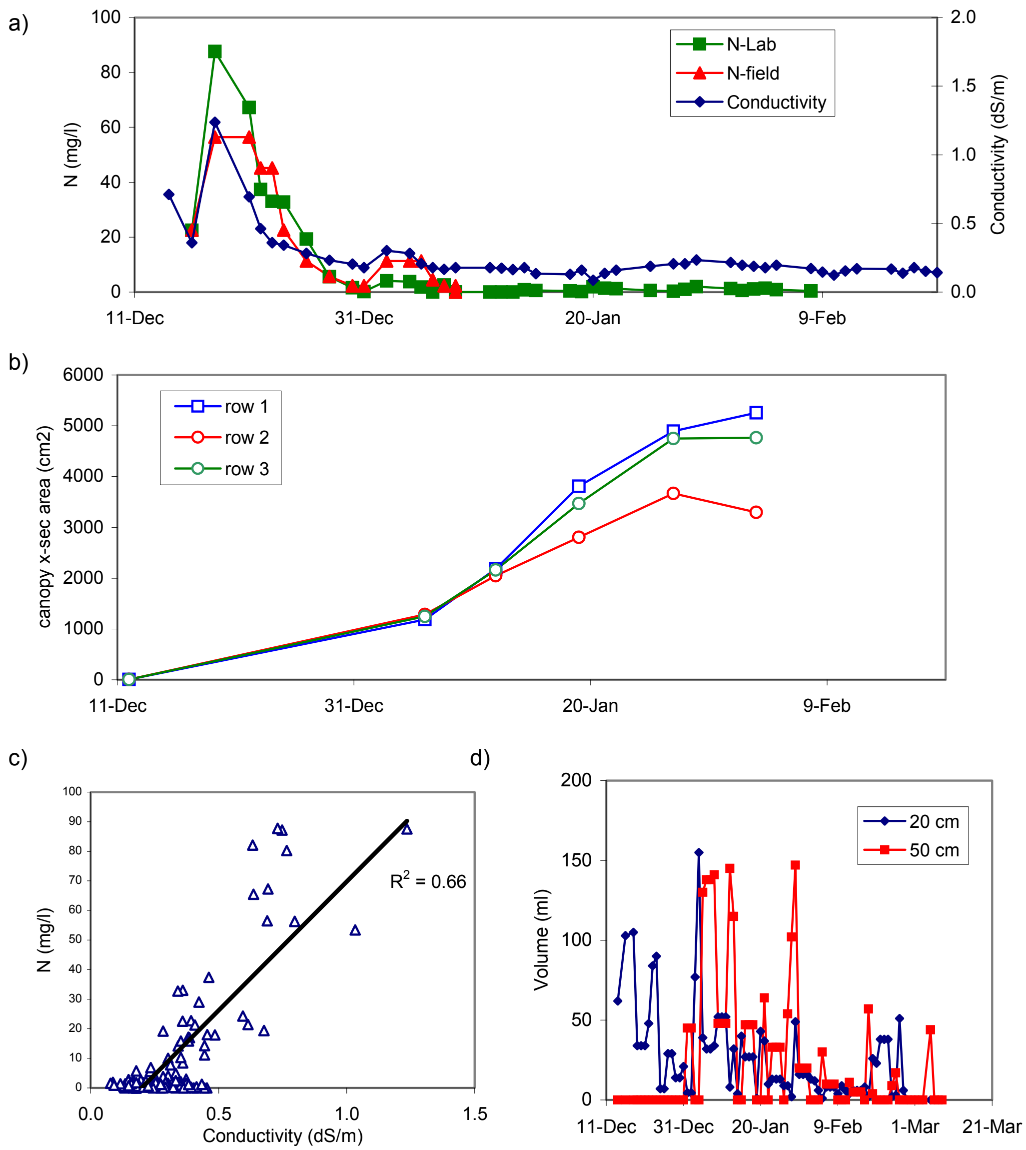


Figure 6 a) The nitrate concentration measured in the laboratory (auto analyser), field (nitrate test strips) and the conductivity of solution from row 1
b) The cross sectional area of the tomato canopy
c) Regression analysis of all mineral-N and conductivity measurements at 20 and 50 cm
d) Volume of soil solution extracted from storage reservoir

Conclusions

1. Plant performance was dominated by the interaction between water management and N availability. Best growth was obtained with the least water.
2. Nitrate test strips or soil solution conductivity could be a substitute for laboratory analysis providing we have occasional cross checks with laboratory measurements.

Canberra: Nitrate leaching in turf

Aim to monitor soil solution collected by FullStops using nitrate test strips and a nitrate electrode under sprinkler irrigated turf
to evaluate the vertical distribution of nitrate and soluble salts

Setup

This experiment was run as a pilot study a year before the current project was funded and is included here to provide a contrasting data set to the above. At the time of the experiment we did not have modified FullStops with the storage reservoirs, but were able to extract some solution directly from the cell housing the float switch immediately after irrigation.

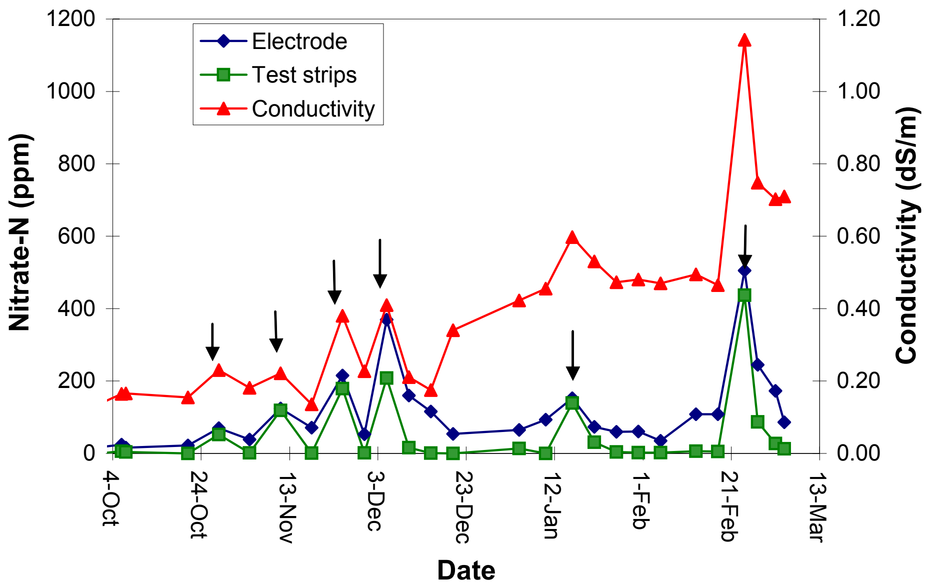
FullStops were installed in 1997 into turfgrass at 15, 20, 30, 50 and 100 cm replicated four times. Irrigation commenced automatically every five days and was terminated automatically when three of four detectors at 15 cm had tripped. A total of 135 Kg N ha^{-1} was applied in six side-dressings as KNO_3 injected into the irrigation water. Dressings were made on 25 Oct at 10 kg ha^{-1} and on 11 Nov, 25 Nov, 5 Dec, 16 Jan and 24 Feb at 25 kg ha^{-1} as shown by the arrows in Figure 7. Water samples were removed from the four 15 cm detectors immediately after each irrigation. The conductivity of the solution was measured using a Horiba conductivity meter. Nitrate concentration was measured using a Cardy nitrate electrode and Merck nitrate test strips. All three measurements can be made with a few drops of solution and give immediate readings, so no storage or dilution of samples was required.

Results

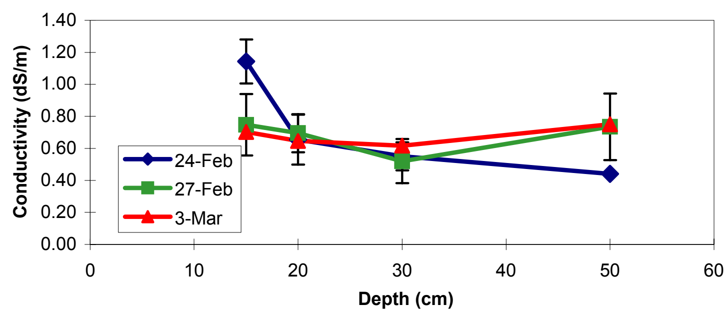
The Cardy nitrate electrode always gave higher readings than the nitrate test strips (Figure 7a). Both systems proved reasonably reliable using standard solutions in the laboratory, but the Cardy nitrate electrode tended to become unstable shortly after calibration. Almost no soil nitrate was present following the first two irrigation events before the first fertiliser application on 27 October. Subsequent fertigation events were clearly recorded in the FullStop samples. The nitrate peaks increased over the first four applications (note the first application was at a lower rate). This suggests that soil nitrate may be building up, but concentrations at the irrigation following fertigation (7 days later) had returned to very low levels. The last two fertigation events (January and February) show a slightly different response. There was some residual N collected in the leachate from the irrigation event following fertigation; this may have been due to the slower growth of this cool-season grass in mid summer and hence a lower demand for N.

Conductivity readings were well correlated with nitrate readings for the first twelve irrigation events (to 15 Dec; r^2 =0.86). Thereafter the conductivity readings climbed, although fertigation events were still evident from the conductivity trace. Nevertheless, conductivity could not be used as a surrogate for nitrate availability even with excellent quality water. We presume the increase in conductivity relates to the build up of potassium in the soil. Only KNO_3 was added to the soil which has a K:N ratio of 2.8:1. Most grasses have a K:N ratio in the range 2:3, so potassium was applied to excess.

a)



b)



c)

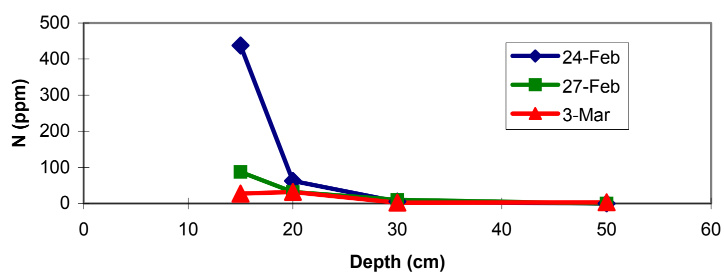


Figure 7 a) Nitrate measured by test strip and Cardy electrode and conductivity of solution in the FullStop cell. Arrows denote time of fertigation
b)change in conductivity after irrigations on 27 Feb and 3 March
c)change in nitrate concentration after irrigations on 27 Feb and 3 March

Figures 7b and c shows the movement of solute through the profile before and after an irrigation event. In order to obtain samples to 50 cm it was necessary to ensure the soil profile was fully wet so that a wetting front terminated at 15 cm would redistribute to the 50 cm detector and give a sample. This was achieved by shortening the irrigation interval. Fertiliser was applied in the irrigation water on 24 February and a high nitrate concentration and conductivity was recorded in the leachate at 15 cm. The next irrigation (27 February) showed the movement of nitrate and salt through the profile. The conductivity profile showed considerable leaching of ions from 15 to 50 cm. The nitrate test strip results showed that nitrate was not the anion involved.

Conclusions

1. Fullstops give a sound overview of nitrate availability and movement through the profile
2. Conductivity measurement mirrored nitrate availability in the short term but not the longer term.

Canberra: Irrigation with saline water and salt leaching

Aim to irrigate with saline water and monitor salt in the root zone
to compare periods of rapid leaching as measured by FullStops and TDR

Setup

The experimental setup was as above, except that the four detectors at 15 cm were replaced with modified versions. In one replicate modified detectors were also placed at 30 and 50 cm. The turf was irrigated from a sprinkler system operating from the four corners of the plot. The irrigation was programmed to begin at 9:30 am six days after a wetting front had last been detected (as a result of rain or of the previous irrigation) and to terminate when three of the four detectors at 15 cm depth recorded the arrival of the wetting front.

Salt was added to irrigation water from 11 January through a venturi apparatus to give a water concentration of 1.5-2 dS m^{-1}. The Fullstop reservoirs were emptied after each irrigation or rainfall event and the conductivity of the soil solution recorded.

Time Domain Reflectometry probes are located along side each FullStop to evaluate their accuracy in recording periods of rapid drainage. TDR was also used to continuously monitor the soil salinity.

Results

Figures 8a and b show the TDR traces from two of the four replicates and the time when the FullStops were activated. On three occasions rain events pushed wetting fronts below 1 m. FullStop output clearly demarcated the times when water was draining rapidly through the profile. Irrigation as controlled by FullStops (Figure 8c) was accurate in the sense that soil water content at 15 cm was largely maintained between 0.2 and 0.25 m^3m^{-3} whereas the wetting fronts did not penetrate to 30 cm.

Salt monitoring by TDR showed a slight build up before and dissipation after the mid-late January rains (Figure 9a). A second build up above 30 cm occurred in March followed by leaching due to rain and accumulation at 50 cm. The wetting front detectors were more responsive to the changing salt levels than the TDR (Figure 9b), possibly because the mobile fraction had a salt concentration closer to that applied in the irrigation water. Unfortunately the rain prevented the soil solution reaching the threshold levels (>2 dS m^{-1}) and did not permit evaluation of controlled leaching by irrigation.

Conclusions

The accumulation of salt as a consequence of saline irrigation and dissipation through rain were easily monitored by the FullStop method.

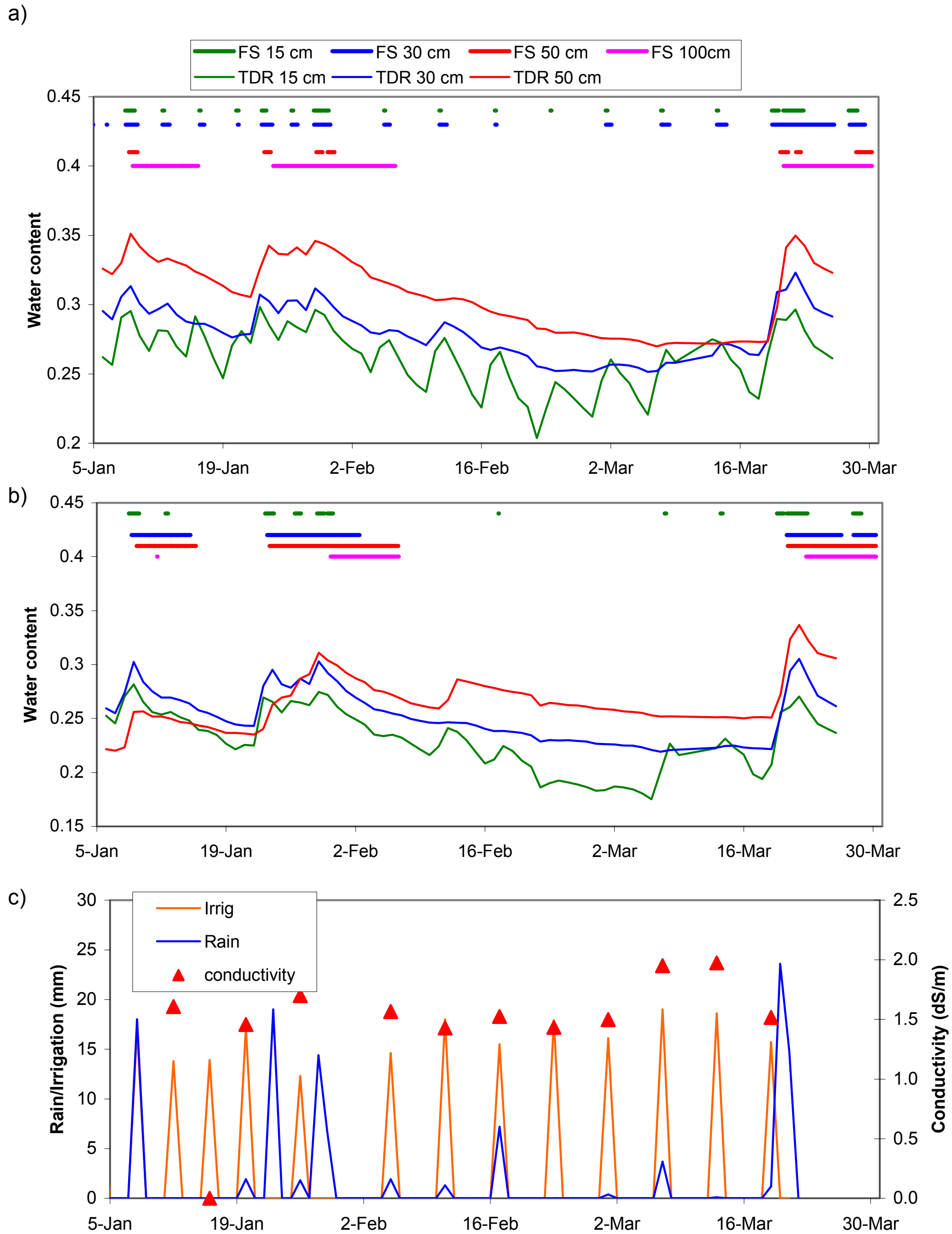


Figure 8 a) TDR traces and periods when FullStops were activated at 15, 30, 50 and 100 cm
b) Replicate 2 (of 4) of above FS = FullStop
c) Daily rainfall and irrigation and the conductivity of the irrigation water

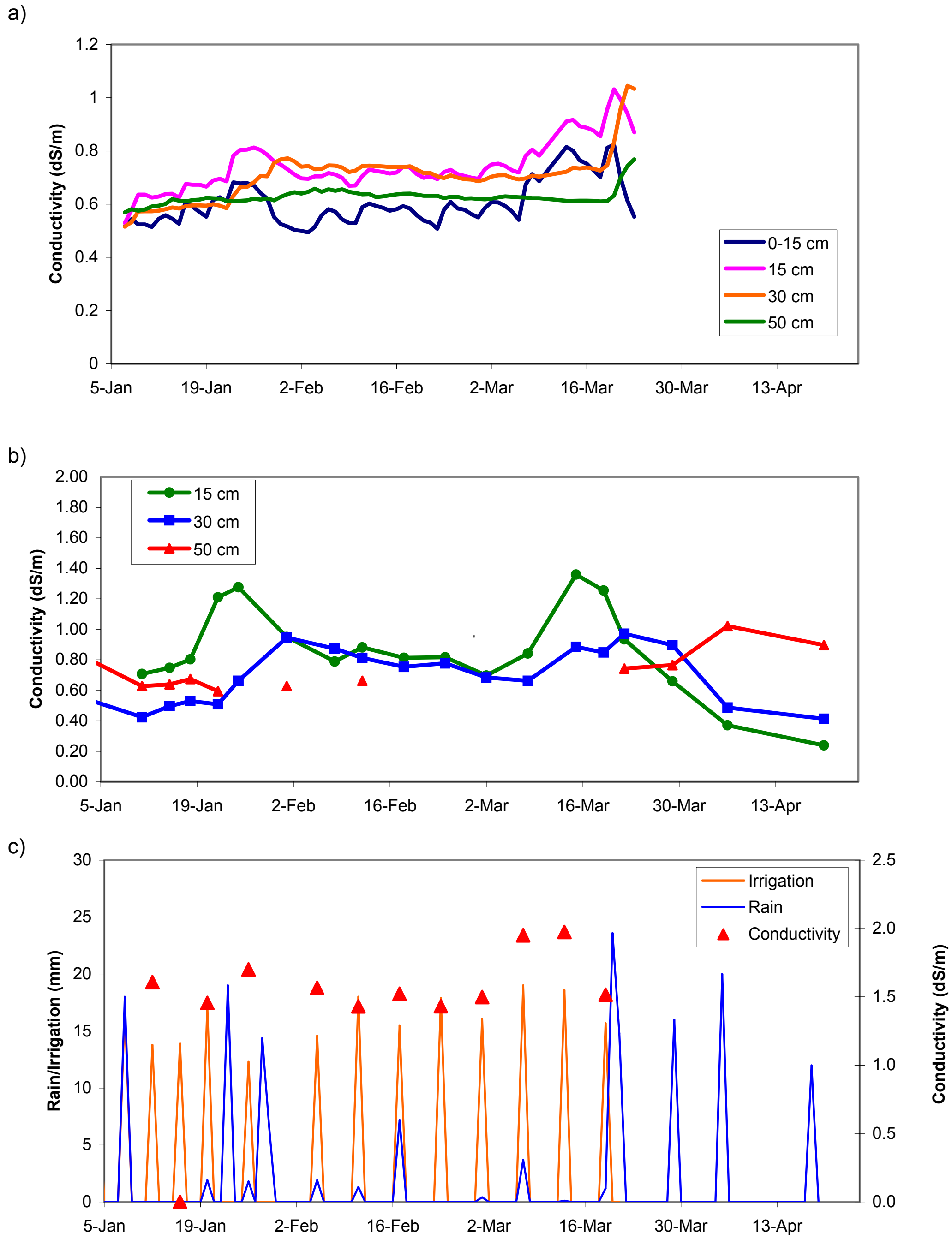


Figure 9 a) Conductivity as measured by TDR
b) Conductivity measured by FullStops at 15 cm, 30 and 50 cm
c) Daily rainfall and irrigation and the conductivity of the irrigation water

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