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MICRO-IRRIGATION: ADVANCES IN SYSTEM DESIGN AND MANAGEMENT

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When to turn the water off: scheduling micro-irrigation with a wetting front detector

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Abstract The science of irrigation scheduling is well advanced, but the field application of this knowledge among irrigators is limited. Case studies are presented to show why irrigators may fail to adopt or persevere with traditional irrigation scheduling methods. This paper describes a funnel-shaped wetting front detector that is buried at an appropriate depth in the root zone. As a wetting front moves into the funnel of the detector, the water content increases due to convergence, so that the water content at the base of the funnel reaches saturation. The free water produced is detected electronically and this provides the signal to stop irrigation. Since the philosophy of drip irrigation in most cases is to supply water little and often, the "when to turn the water on" question becomes redundant and knowing when to turn the water off is more useful. Two further case studies demonstrate the benefits of scheduling micro-irrigation using wetting front detectors. The detectors retain a water sample from each irrigation event and this was used to monitor nitrate movement in and below the root zone.

Introduction

The scientific tools the irrigator needs to accurately manage water are well developed. Field monitoring of soil suction began in the 1930s with the development of the tensiometer (Richards and Neal 1936), followed by water content measurement using neutron scattering (Gardner and Kirkham 1952) and more recently the development of precision instruments that measure the dielectric property of soil (e.g. White and Zegelin 1995). There are a number of surrogate methods for measuring crop water status, one of the simplest field-based methods being canopy temperature (Jackson et al. 1977). Crop water requirements can be estimated by measurement of potential evaporation and empirically derived crop factors that account for leaf area development. Computer models that predict crop growth and evapotranspiration from soil and climate data are a more sophisticated version of this method (Allen et al. 1998).

Most irrigators do not use these tools in any systematic way (Meyer and Nobel 1993; Australian Academy of Technological Sciences and Engineering 1999). There may be two reasons for poor adoption. Either the above tools do not work reliably in the field, or farmers cannot justify the time and expense of collecting, interpreting and implementing the information they provide.

This paper presents three case studies in which horticultural crops were irrigated using the soil tension, soil water content and crop factor methods. The case studies demonstrate the difficulties experienced when translating information to a decision on when and how much to irrigate. These experiences stimulated a re-examination of what would be the simplest information on which to base a credible irrigation decision and the cheapest and most robust way of collecting it.

This paper tests the hypothesis that knowing the position of a wetting front is the simplest information that could be used to improve irrigation management. Such information enables the irrigator to apply sufficient water to replenish most of the root zone, but not so much that water and nutrients move below the root zone. The device used to detect wetting fronts is a funnel-shaped container that is filled with soil and buried at an appropriate depth in the soil. When a wetting front enters the funnel the water content increases due to streamline convergence. Free water produced at the base of the funnel then flows through a filter into a cavity and activates a float switch (Stirzaker and Hutchinson 1997; Hutchinson and Stirzaker 2000; Stirzaker et al. 2000).

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Two further case studies are given which evaluate the wetting front detector method of managing micro-irrigation.

Case study 1: Scheduling by soil suction

The tensiometer is easy to understand and use, does not require calibration for soil type, is relatively inexpensive, and measures soil tension, the variable most closely linked to the water status of the crop. Despite these advantages, it can be difficult to use in practical situations, as illustrated in Fig. 1. The data come from a drip-irrigated melon crop grown near Griffith, NSW, Australia (34°18′S, 146°04′E), where six tensiometers were used to schedule irrigation on a sandy clay loam soil (Charlesworth 2000). The drip tape was buried at a depth of 200 mm and the tensiometers were placed with the ceramic cup 50 mm above and 50 mm laterally away from the drip tape. The aim was to irrigate so that the soil suction was maintained between 10 and 40 kPa. At wetter (lower) suctions the crop does not need to be irrigated and at drier (higher) suctions the crop may already be experiencing some stress. Figure 1 shows that the field was some mixture of too wet, optimal and too dry throughout the season. There was only one day during the season (11 February) when all six tensiometers were within the optimal range.

The data reflect the variability in soil properties, plant growth and irrigation uniformity common to all soil-based measurements. However, the problem is particularly acute in the case of the tensiometer because of the steep relationship between water content and suction and the fact that air is drawn into the instrument at suctions greater than 60 kPa. A delay of just one day can see suctions rise from 30 to 60 kPa. Such rapid changes often catch the irrigator by surprise and the irrigator may also have the additional chore of purging the tensiometer of air.

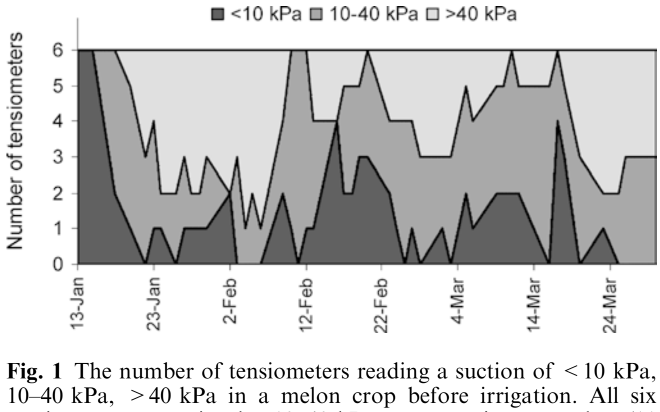

Fig. 1 The number of tensiometers reading a suction of < 10 kPa, 10–40 kPa, > 40 kPa in a melon crop before irrigation. All six tensiometers were in the 10–40 kPa zone on just one day (11 February)

Case study 2: Scheduling by soil water content

Continuous measurement of soil water content such as time domain reflectometry (TDR) would seem the most desirable information for the irrigator. When the soil water content falls below some preselected refill point the soil is irrigated to bring a specified depth of soil back to the drained upper limit. In practice, calibration of sensor equipment together with local experience is required to define both the refill point and the drained upper limit. Spatial variability again makes the information difficult to interpret, as illustrated in Fig. 2. The data depicting water content with time come from four TDR probes (Zegelin et al. 1989) at the same depth (150 mm) all within a radius of 4 m under a uniform canopy of turfgrass. If a refill point of 0.2 m^3m^{-3} was selected, then site 1 calls for irrigation on 17 October, site 2 on 19 October and site 3 not at all. A practical way around this problem is to normalise each measured site to a drained upper limit and lower limit and irrigate at some specified percentage depletion. Nevertheless it remains questionable whether precision measurement to the nearest 0.2% is necessary for scheduling when normal variability in soil properties, plant growth and water application induces differences of several percentage points between sites.

Identification of excessive irrigation from continuous measurement of soil water content can also be difficult. Few irrigators understand that water can be moving into a layer of soil at the same rate as it is moving out, and make the mistake of interpreting a fairly flat water content versus time trace as evidence of no drainage.

Case study 3: Scheduling by crop factors

Measurement of atmospheric demand sidesteps variability of soil water content and treats the crop as a uniform transpiring surface. Figure 3 shows the growth of a drip-irrigated processing tomato crop irrigated using the pan evaporation/crop factor method on a loam soil near Camden, NSW, Australia (34°04′S, 150°40′E). The aim of the experiment was to use as little water as

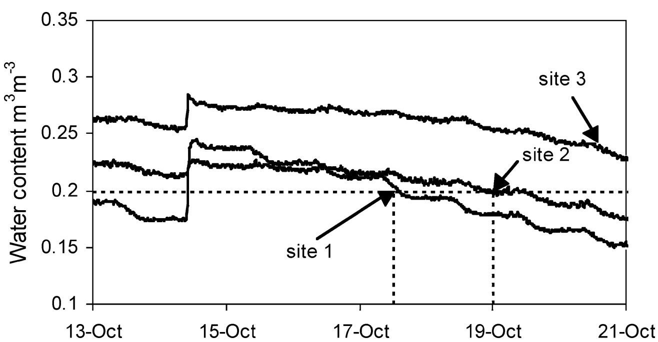

Fig. 2 The water content measured by TDR during a drying cycle and the day to irrigate based on a refill point of 0.2 $m^3\ m^{-3}$

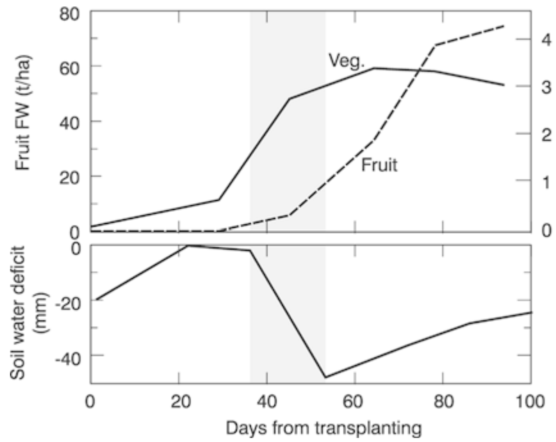

Fig. 3 The seasonal course of vegetative and fruit growth of a drip-irrigated tomato crop. Crop factors did not match the exponential growth period, causing increasing water deficits coinciding with the most yield-sensitive stage of growth (*shaded*)

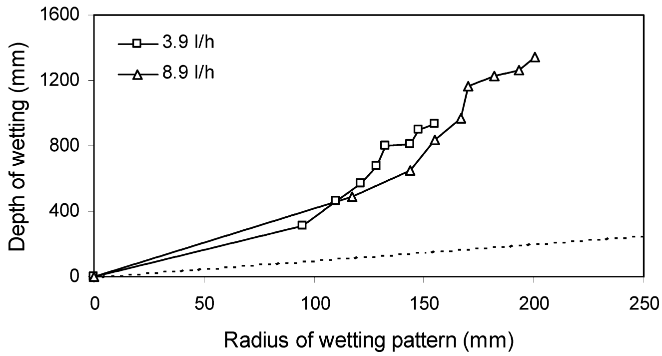

Fig. 4 The radius of a wetting pattern from drip irrigation plotted against the estimated depth of the wetting pattern for fast and slow emitters on a loamy sand soil. The *dotted line* represents a hemispherical wetting pattern where the depth is equal to the radius at the surface

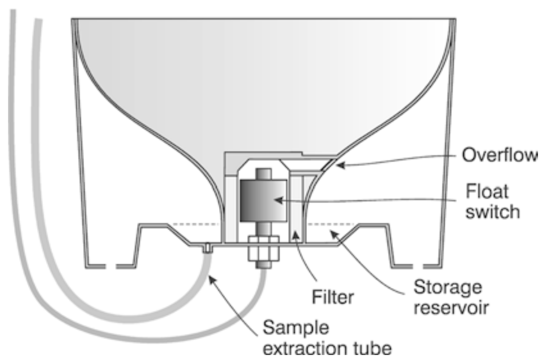

Fig. 5 A schematic of the wetting front detector showing the filter, cavity, float switch and overflow reservoir for collection of soil solution

possible. However independent monitoring by neutron probe revealed that water deficits occurred at the onset of the exponential growth stage because the crop factor was too low. The crop factor was adjusted upward, but not sufficiently to match the rapidly increasing leaf area, so the period of deficit lasted for several weeks. The timing of water stress coincided with flowering and early fruit growth, when the greatest yield penalties are exacted (Rudich et al. 1977).

This example highlights three difficulties with this method in its practical application by farmers. First, the crop factors are not always transferable from district to district or season to season and depend heavily on the irrigation method used. Second, errors in the crop factor method are cumulative, so that the farmer tends to consistently over-irrigate or under-irrigate. There is no feedback until the crop wilts or is waterlogged. Third, it requires knowledge of the application rate of the irrigation system, the size of the field, the potential evaporation and a calculation to give the correct irrigation run time. Although each step is trivial, it is rare to find a farmer who consistently collects and applies all the information.

Wetting front detector

The impetus for developing a simple wetting front detector came from a project with the aim of promoting water-saving technologies for resource-poor farmers, carried out at the Tompi Seleka College of Agriculture in the Northern Province of South Africa (24°57′S, 29°13′E) (Stirzaker et al. 1996, 2000). The soil was light-textured (sand 88%, silt 5%, clay 7%) and contained a gravel layer at about 400 mm depth that restricted root growth. A readily available water-holding capacity of just 16 mm in a semi-arid climate made this a challenging site for irrigation scheduling.

Drip irrigation was difficult to manage at this site; in particular the compromise between making the wetting pattern as wide as possible without pushing the wetting front deep into the gravel layer. The radius of the wetting pattern at the surface from 3.9 and 8.9 l h^{-1} emitters was measured at 10-min intervals. The depth of wetting was estimated on the crude assumption that the water content increased by 0.07 m^3 m^{-3} from before to immediately after irrigation, and that the water content was uniform within a cylinder of soil around the emitter. Figure 4 shows that gravity was dominating the movement of water before the wetting patterns had a radius of 100 mm at the surface. Wetting fronts reached 400 mm after 20 and 10 min for the slow and fast emitters, respectively, and this was before redistribution of water after irrigation ceased. Given the low water-holding capacity of the soil, irrigation had to be frequent, so the key issue was when to turn the water off.

The design of the wetting front detector is shown in Fig. 5. The detector is a funnel-shaped container that is buried open end up in the soil and which works on the principle of convergence. As a wetting front moves into the wide opening of the funnel, the flow lines are converged, so that the water content increases towards the base of the funnel. The dimensions of the funnel are such that the soil at the base becomes completely saturated. The free water produced at the base of the funnel flows through a filter into a chamber where it activates an electrical float switch (the detector is "tripped"). The float switch may be connected to an alarm, irrigation controller or connected in series with a solenoid valve so that the irrigation is switched off automatically.

As the soil suction surrounding the detector falls following irrigation, water is withdrawn from the chamber by capillary action. The float falls and the device is automatically "reset". Because the height of the funnel is 100 mm, water is drawn out of the funnel once the soil suction outside the funnel increases to just over 100 mm or 1 kPa.

About 20 ml of liquid water is required to trip the float switch. However in almost all cases more water than this is produced. The excess water overflows from the chamber housing the float switch and is stored in a separate reservoir at the base of the detector (Fig. 5). This water can be extracted using a syringe via an extraction tube and can then be used for nitrate or salt monitoring. Whether or not the sample is collected does not affect the operation of the float switch – excess water collected from the reservoir overflows into the surrounding soil.

An example of how the detector works is shown in Fig. 6. The detector with a funnel diameter of 200 mm was buried in a drum of fine sand with the lip of the funnel at a depth of 150 mm and the float at a depth of 250 mm. Four equally spaced drippers were placed on the surface around the detector in a ring with 300 mm diameter. Flow to the emitters was maintained using a bubble tube at the slow rate of 0.15 l h^{-1}, giving an application rate over the surface area of the drum of 2.5 mm h^{-1}. Tensiometers were positioned with the ceramic cup centred at a depth of 200 mm in the funnel above the float switch (position 1) directly beneath the emitter (position 2) and 150 mm to either side of the emitter (Fig. 6a, position 3). Measurements were made using a portable pressure transducer following the method of Cresswell (1993).

The wetting front detector tripped (free water detected) 145 min after irrigation commenced (dotted line in Fig. 6b), during which time 6 mm of water was applied. The suction at all three positions fell until the water was turned off and then gradually rose as redistribution occurred. The minimum suction directly beneath the emitter was 95 mm (0.95 kPa). At position 3, 150 mm away from the emitter, the minimum suction was 150 mm (1.5 kPa). At position 1, 150 mm away from the emitter but inside the funnel, the suction fell to 10 mm (0.1 kPa). Since the measurement point was approximately 50 mm above the float, there was a 40 mm high water table inside the funnel; sufficient to cause the float to rise. Put another way, the wetting front away from the emitter (position 3) was moving at a suction of 1.5 kPa (150 mm). The detector elevated the suction to greater than zero and thus produced the free water that activated the float.

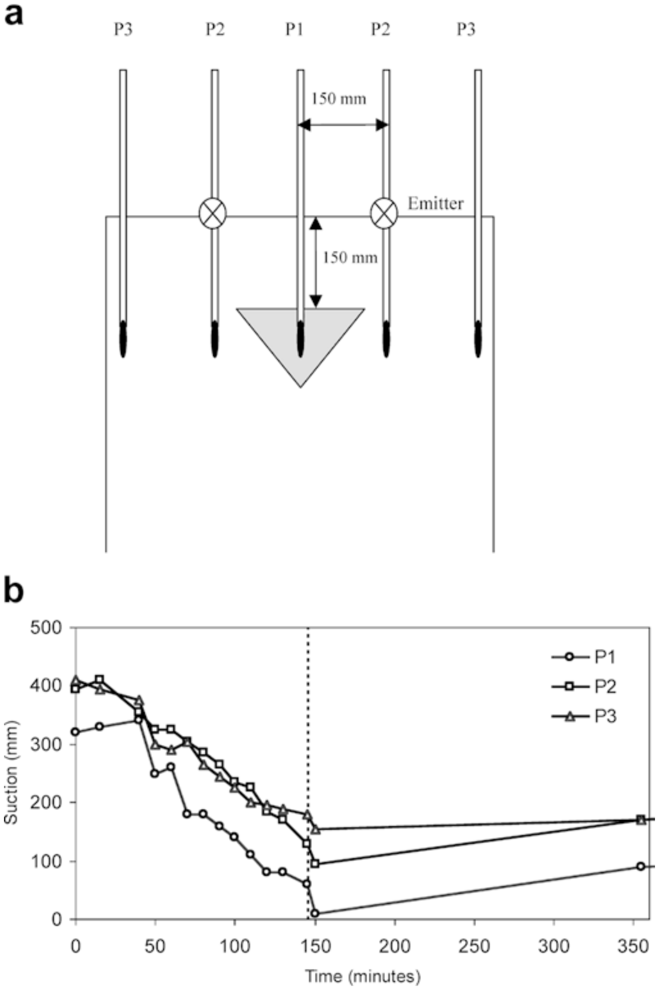

Fig. 6 a The location of tensiometers around a buried detector. Position 1 (*P1*) was inside the detector, position 2 (*P2*) directly beneath an emitter and position 3 (*P3*) 150 mm away from the emitter. **b** The change in soil suction during irrigation inside and outside the detector. The *vertical dotted line* shows the time the float detected water and the irrigation system was turned off

Case study 4: Managing drip irrigation with wetting front detectors

The wetting front detectors were used to schedule irrigation to a drip-irrigated capsicum crop grown near Gosford, NSW, Australia (33°25′S, 151°18′E) on a 300 mm deep sandy-loam topsoil overlying a rocky sandy-clay subsoil. Two detectors were placed with the float switch at 300 mm depth (shallow detectors) and two at 700 mm depth (deep detectors). The shallow detectors were connected to a solenoid valve via a controller, so that the solenoid valve was switched off when the wetting front reached the detectors. For the first 2 weeks (18 January –1 February), irrigation was scheduled daily to the newly planted seedlings and shut off automatically when the wetting front had reached both shallow detectors, or when 2 h had elapsed, whichever occurred first. For the remainder of the season the

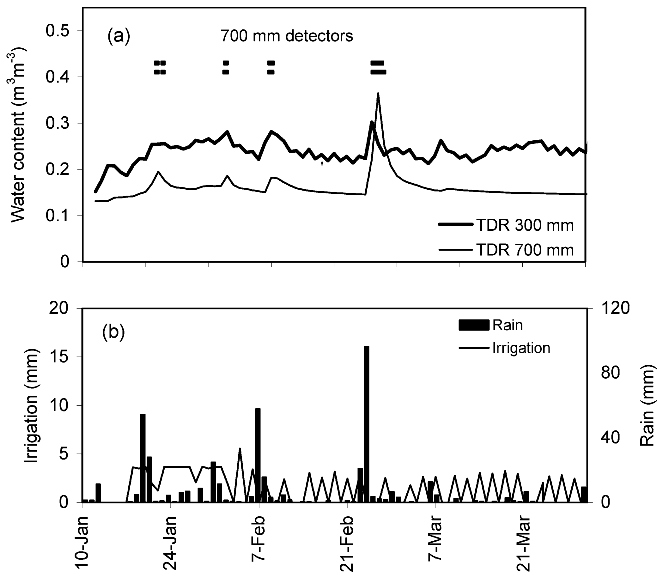

Fig. 7 **a** The *continuous lines* show the average water content (*TDR*) at 300 and 700 mm depths from a drip-irrigated capsicum crop. The *horizontal broken lines* at the top of the figure show the times when the deep detectors (two replicates) recorded water (*start of the line*) and the time the water was withdrawn from the funnel by capillary action (*end of the line*). **b** the amount of irrigation and rain received during the growing season

solenoid valves were opened at the same time every second day and closed when the first of the two shallow detectors had detected the wetting front.

TDR probes were inserted horizontally adjacent to the detectors at depths of 300 and 700 mm. The irrigation management was run automatically without any intervention and the times that the detectors tripped and reset were logged. Figure 7a shows the average daily water content measured by TDR at the depths of the shallow and deep detectors and Fig. 7b shows the amounts of rainfall and irrigation.

The season was unusually cool and wet, with 431 mm of rain and 115 mm of irrigation during the growing season. The maximum amount of irrigation allowed by the detectors on any one day was 5.6 mm with an average application of around 3 mm (averaged over the row and inter-row area). The soil water content, measured by TDR, never fell below 0.22 m^3m^{-3} (Fig. 7a), whereas it fell to 0.16 m^3 m^{-3} in the adjacent sprinkler irrigated treatment not controlled by wetting front detectors. The solid horizontal lines at the top of Fig. 7a show the time that the deep detectors tripped (the start of the line) and reset (the end of the line). Whereas the two shallow detectors recorded the arrival of wetting fronts 41 and 33 times during the period shown in Fig. 7, the deep detectors tripped just five times, and each time it was in response to rain, never irrigation. This is also shown by the TDR trace at 700 mm, which responded only to rain and not to irrigation (Fig. 7b).

In this soil, root growth was markedly less in the rocky subsoil. The aim was to keep the topsoil well watered and to minimise the amount of irrigation water reaching the subsoil. The former objective was achieved by automatically turning the water on every second day and allowing the shallow detectors to terminate the irrigation. It is difficult to evaluate the latter objective from TDR data alone. Although the TDR gave much more information about soil water status than the detectors, it is hard to see how, armed with this extra information, irrigation management would have been improved.

Case study 5: Managing water and nitrogen using wetting front detectors

This study was similar to the above except that the conductivity and nitrate content of water stored in the collection reservoir after each rainfall or irrigation event was measured. Detectors were buried at 200 mm (shallow) and 500 mm (deep) under drip-irrigated tomatoes in Canberra, Australia (35°18′S, 19°08′E). Instead of the first of two shallow detectors closing the solenoid to the plot, as in the study above, each shallow detector controlled its own row. In this case the float switch in the detector was wired in series with an irrigation controller. The controller was programmed to provide 13 mm (2 h) of irrigation each day. If the wetting front reached the shallow detector before this time, the float rose, cutting off power to the solenoid, so that the valve closed. Again there was no manual intervention in the irrigation: the "on" was set by a controller and the "off" by the detectors.

Each day the amount of irrigation to each row was logged and solution was collected from the overflow reservoir at the base of the shallow detector (Fig. 5). If the wetting front reached the deep detectors, following redistribution of water after the irrigation ceased or rainfall, the time of arrival was logged and solution collected. The 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 using a watering can. Conductivity was measured with a Horiba B-173 portable salinity meter and nitrate measured by nitrate test strips and segmented flow analyser (Alpkem 1992).

Irrigation occurred on 78 days and was terminated when the wetting front reached the shallow detector or after 2 h (13 mm), whichever occurred first. Row 1 received a total of 255 mm and row 2 335 mm during the period shown in Fig. 9c. Both rows received 99 mm of rainfall. The suction measured by tensiometers at a depth of 200 mm recorded 8 days drier than 50 kPa in row 1 and 2 days drier than 50 kPa in row 2 (Fig. 8b). The solid lines in Fig. 8a show the time period when water was present in the deep detectors. During the early part of the season, from 20 December to 20 January, the deep detector in row 2 frequently detected water, meaning that the soil suction was wetter than 2 kPa. After this period the deeper detector was rarely

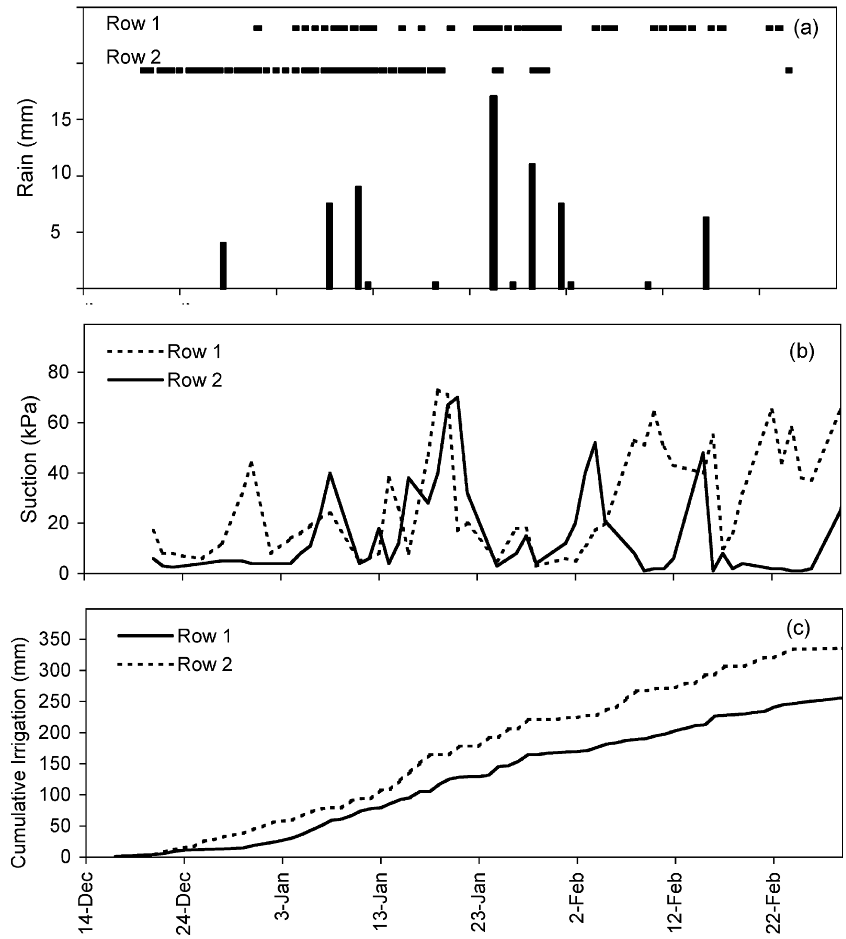

Fig. 8 **a** The *horizontal broken lines* at the top of the figure show the times when the deep detectors in row 1 and row 2 recorded water (*start of the line*) and the time the water was withdrawn from the funnel by capillary action (*end of the line*). The *vertical bars* show the rainfall received by the tomato crop. **b** The soil suction at 200 mm depth. **c** The cumulative irrigation

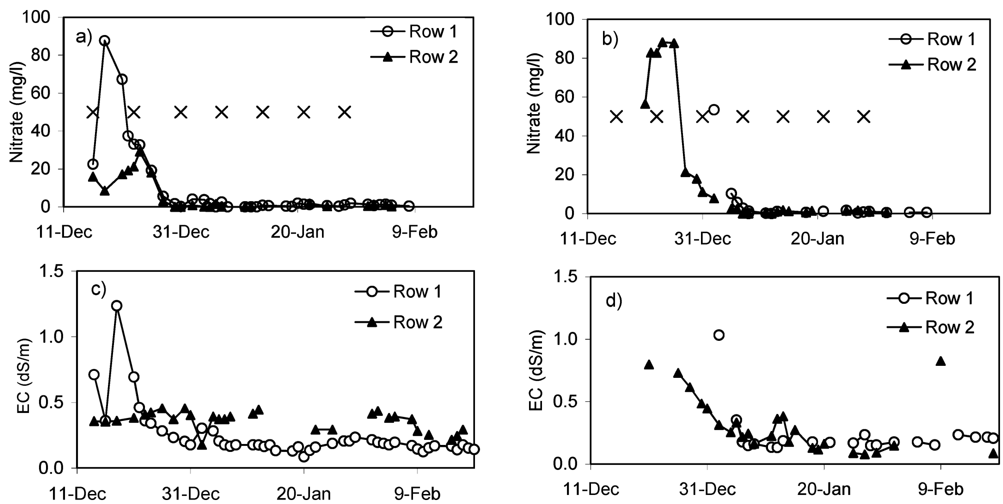

Fig. 9 **a** The nitrate concentration measured at 200 mm. *X* marks the time of fertigations. **b** The nitrate concentration measured at 500 mm. **c** The electrical conductivity (*EC*) measured at 200 mm. **d** The EC measured at 500 mm

activated. In contrast, the deep detector in row 1 was activated less often during the beginning of the season and more often during the middle period, particularly when rainfall and irrigation occurred on the same day.

It is important to note that the deep detectors were activated by irrigation even though the water was turned off when the wetting front reached 200 mm. Once the profile was wet between 200 and 500 mm depth, any wetting front reaching 200 mm continued to move through the profile. Clearly the irrigation interval was too short during the early crop stages and the root system had not yet moved below 200 mm. The fact that wetting fronts penetrated to 500 mm means that the crop was most likely to have been over-irrigated, although rain plus irrigation totalled just 376 and 450 mm in rows 1 and 2, respectively. From the perspective of wasting water, such low seasonal water applications do not cause alarm. However the composition of the leaching water was of much greater concern.

Figure 9a shows the nitrate concentration of water from the reservoir of the shallow detectors (fertigations marked by X). During the early crop stages much more nitrate was detected in row 1, which received less water than row 2. The opposite was true at 500 mm (Fig. 9b). In the latter case, the high nitrate levels at depth in row 2 show that nutrients were being pushed out of the root zone. The fact that the wetting front did not reach 500 mm in row 1 until late December means that much of the soil nitrate was being stored in the 200–500 mm layer and remained accessible to the crop.

Very little nitrate was detected in either row after 28 December at 200 mm and after 6 January at 500 mm. The implications for irrigation and nitrogen management are clear. A small difference in irrigation between rows 1 and 2 of around 30 mm had a large effect on nutrient dynamics. Row 1, which received less water, produced 30% more fruit. Lastly, fertigation should have commenced 3 weeks later, after the soil supply of nitrate had been depleted.

Figure 9c, d shows the conductivity of the water removed from the detectors at each depth. The shape of the conductivity traces with time are very similar to those for nitrate, indicating that a rapid and cheap conductivity test could be an indicator of whether leaching was occurring. Such an indicator could not be used if the irrigation water was of low quality and salts accumulated in the root zone. In this case the conductivity could be used to monitor the leaching fraction. Nitrate was also monitored using nitrate test strips (Merckoquant 10020 nitrate test strips; Merck, Germany). The nitrate trend measured by test strips was the same as that from the laboratory analysis and since ammonium was a small proportion of the mineral N, the test strips provided the same message as the laboratory analysis. A small amount of over-irrigation at the start of the season caused rapid leaching and the fertigation schedule should have been delayed until the soil supply of nitrate had been drawn down.

Discussion

Numerous experiments have demonstrated that scheduling with tensiometers, capacitance or TDR probes and atmosphere-based methods improve irrigation practice. However case studies 1–3 highlight some of the reasons why irrigators may fail to adopt or persevere with such methods. Tensiometers often move through their working range faster than an irrigator can respond (Fig. 1). Spatial variability brings into question the value of precision for soil water content measuring (Fig. 2). The cumulative error in atmosphere-based methods introduces uncertainty (Fig. 3).

Soil-water monitoring equipment can ensure that the soil is maintained "wet", even with minimal calibration. This does not, however, solve the problem of over-irrigation and leaching on well-drained horticultural soils. Even with sophisticated continuous water content measurement equipment, it is difficult to differentiate between plant uptake, redistribution within the root zone and drainage from the profile. A key strength of the wetting front detector is its ability to quickly identify leaching of water and nutrients (Figs. 8, 9).

An excessive focus on precision in irrigated horticulture may be misguided because even in well-managed systems there are substantial losses of water and nutrients below the root zone (Stirzaker 1999). At the site where case study 4 was conducted, trials reproducing "district farmer practice" calculated that 633 kg N ha^{-1} was leached in an 18-month 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). 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. Against this background, any tool that helps the farmer cut back applications of water and nutrients should have some impact.

The problem of variability is common to all soil-based methods of scheduling. Schmitz and Sourell (2000) evaluated three commercially available soil water sensors by placing 25 of each sensor in a 700×700 mm grid. The same type of sensors within close proximity frequently differed by 100% (one sensor recorded 50% available water and the other 100%). In the case of the wetting front detector, one method of managing variability is to bury a number of detectors at the same depth and connect them to a controller. The controller allows the user to specify the number of detectors that should trip before irrigation is cut off. Thus the variability issue is turned into a risk management strategy, with the user deciding what degree of under- or over-irrigation is tolerable over parts of a field for a given crop and stage of growth.

Limitations to the use of the detector method include the importance of matching the placement depth and frequency of irrigation with the soil type, crop type and stage of growth. If detectors are too deep or irrigation too frequent then redistribution of water after irrigation may carry water below the root zone. Conversely if detectors are too shallow or irrigation too infrequent, the soil may dry excessively between irrigations. For sprinkler irrigation, detectors should be placed about halfway down the root zone for light soils and two-thirds of the way down the root zone for heavier soils (Hutchinson and Stirzaker 2000). For drip irrigation, the minimum depth should be the radius of the wetting pattern at the surface. Disturbance during installation may be a problem for permanent crops in some soils, and in all cases there will be a settling down period as the roots re-establish in the disturbed area. Installation is less difficult for annual crops because the detector placement is frequently within the ploughed layer. The detector is not suitable for more specialised practices, such as regulated deficit irrigation (Chalmers et al. 1981), but may be suited to partial root zone drying (Loveys et al. 1998) because part of the root zone is fully replenished each irrigation.

In the experiments described in case studies 4 and 5, detectors were used in "control mode", where a solenoid valve was automatically shut off when the wetting front reached a particular depth. Such an application is not suited to the majority of farmers, who do not have automated systems. Current work is evaluating the wetting front detector in "feedback mode". In this case detectors are placed at two depths, halfway down and towards the bottom of the active root zone. The irrigator predicts the amount of water required by the crop and then observes how deep the wetting front progressed after redistribution has taken place (say 24 h later). The irrigator adjusts the interval or amount applied in the next application depending on whether no detectors, shallow detectors only, or shallow and deep detectors responded the previous time. A simple version of the detector in which the electronic switch is replaced by a mechanical float is ideally suited to this application (Stirzaker et al. 2000).

The principle underlying the wetting front detector method is that the wetting front moves through the soil at a rate dependent on the initial water content (Philip 1969). If the soil is relatively dry before irrigation, the wetting front moves slowly and a long irrigation is permitted. Conversely, if the soil is already wet, the wetting front moves fast and the irrigation event is quickly terminated. The method of irrigation by the position of a wetting front was first proposed by Zur et al. (1994), who used a vertical array of resistance sensors that required considerable investment in electronics and logging equipment. Although providing more information than the detector described here, there is a trade-off in cost and complexity. Similarly the idea of using a buried container to collect solution can be traced back to a history of work with passive soil solution samplers and mini-lysimeters, as reviewed by Litaor (1988) and Paramasivam et al. (1997). The wetting front detector described here combines the features of monitoring the passage of a wetting front and the solutes it contains with minimal hardware requirements.

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