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Research article

# Effects of subsurface drip irrigation rates and furrow irrigation for cotton grown on a vertisol on off-site movement of sediments, nutrients and pesticides

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**Abstract** – Subsurface drip irrigation can reduce off-farm movements of fertilizers and pollutants and improve the water use efficiency of irrigated agriculture. Here we compared the effects of furrow and subsurface drip at different irrigation rates, based on a percentage of daily crop-evapotranspiration rates (ETc), on run-off and off-site movement of suspended sediment, nutrients and pesticides from cotton crops grown on a vertisol. Our results show that furrow irrigation significantly increased suspended soil loss, of 5.26 $t\,ha^{-1}$, compared to that of subsurface drip irrigation at 120% of ETc, of 2.53 $t\,ha^{-1}$, whereas no erosion was recorded with deficit subsurface drip irrigation. Off-site movement of nitrogen in furrow, of 18.63 $kg\,ha^{-1}$, was five times greater than subsurface drip irrigation at 120% ETc. It was much less with 105% ETc (0.37 $kg\,ha^{-1}$) and 90% ETc (0.15 $kg\,ha^{-1}$), and absent for 75% and 50% of ETc. Phosphorus loss from furrow, of 778 $g\,ha^{-1}$, was greater than for the wetter subsurface drip treatments that gave 23 $g\,ha^{-1}$ for 90% ETc and 19 $g\,ha^{-1}$ for 120% ETc. No P loss was recorded from drier subsurface drip irrigation rates. Herbicides such as atrazine and diuron were applied in the year prior to the experiment, but considerable amounts were recorded in furrow run-off in both years, but only at 90 and 120% ETc subsurface drip irrigation in the first year. Concentrations of applied herbicide residues in the runoff exceeded the minimum threshold level for 99% species protection and, although the total amount of herbicide movement was higher in furrow, at times the concentration was greater for wetter subsurface drip irrigation run-off. Residues of insecticides, such as endosulphan applied in a previous year and dimethoate applied in the current years, were recorded in runoff from subsurface drip at 120% and furrow irrigation. Their concentrations in each year exceeded minimum threshold level. Subsurface drip irrigation at 75% ETc offered the best trade-off between off-site run-off, erosion and pesticide movement and yield and water use efficiency.

**Furrow / subsurface drip / run-off / erosion / herbicide/ nitrogen / phosphorus**

## 1. INTRODUCTION

Quality of downstream surface water bodies may be degraded by the runoff of soil, pesticides and nutrients from cropland (Shaxson, 2006). Off-farm movements of soil and associated compounds from cropland is due to irrigation or rainfall-induced surface runoff (Lal, 2008). Subsurface drip irrigation offers tremendous scope to control runoff when compared to furrow irrigation, and to minimize the contamination of downstream water bodies due to irrigated cropping (Jensen et al., 1990). Run-off from cotton fields may carry sediments and nutrients and if not retained and recycled, can move into the riverine systems and ultimately to the ocean. Broadly, water resource regulatory bodies across the globe are insisting that farmers reduce the discharge of contaminants from agricultural fields into surface water bodies and ground water (Bernoux et al., 2006). Common impairments to water quality in agrarian settings allegedly arise from non-point sources such as application of commercial fertilizer, animal manure, pesticides and other inputs used in farms. In order to achieve clean water targets, the agricultural industry needs to adopt farm practices that minimise the impacts of farming on the health of aquatic environments (Kennedy et al., 2001).

Cotton (*Gossypium hirsutum* L.) is highly responsive to irrigation and, therefore, produces a higher and more stable yield and lint quality than the dry land crop (Hearn, 1994). Cotton around the world is predominantly furrow irrigated, and often blamed for heavy applications of fertilisers and pesticides

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(Constable, 2004). Conventional cotton irrigation methods are described as wasteful and produce considerable run-off and leaching of water and pollutants (Carroll et al., 1995). However, use of appropriate irrigation methods and practice of regulated deficit irrigation can greatly reduce the run-off from irrigated crop fields.

As water supply for irrigation becomes more competitive, especially as industrial and domestic sector demands increase as do those for environmental flows, there is a greater need to improve water use efficiency of irrigated cotton. State of the art technologies for water savings in irrigation have been adopted, but not widely, across all farming sectors in Australia. In this context subsurface drip irrigation has a pronounced advantage (Wanjura et al., 1996). The irrigation efficiency for furrow can be poor (56%) (Goyne and McIntyre, 2002) if improperly managed and used on heavy clay soils, compared to sprinkler irrigation (>75%), whereas according to Kruse et al. (1990) subsurface drip can improve irrigation efficiency to 90%.

Water use efficiency of subsurface drip irrigation is enhanced by minimizing run-off and evaporation compared to furrow if installation, site specific designs, maintenance and irrigation management are optimal. We have shown (Bhattarai et al., 2006) the advantages of subsurface drip over furrow for yield and water use efficiency of cotton in a tropical environment. Subsurface drip can also potentially offer a multitude of other advantages by minimizing the off-site movements of run-off, sediments, pesticides and nutrients (Camp et al., 1999) provided crop, soil and climate specific irrigation rates are applied. Reduced disease, insect, and weed infestations have also been reported with subsurface drip irrigation (Camp, 1998).

There is growing interest in the use of subsurface drip irrigation globally, not only because of its ability to increase water use efficiency, but also because of the significant pressure to conserve water resources and the ready access to affordable materials. Field studies in similar soils by Carroll et al. (1995, 1997) evaluated the effect of crop type, rotation and tillage practice as well as furrow length on run-off and soil losses in furrow irrigated cotton. Research works by Connolly et al. (2001), studied the severity of insecticide transport from cotton fields with furrow irrigation. Similarly, Gaynor et al. (2002) and Harman (2004) quantified the run-off and drainage loss of herbicide with furrow irrigation, and implicated a larger off-site movement with increasing furrow irrigation rates.

Water management of subsurface drip irrigation can be manipulated to influence the dynamics of deep drainage (Hutmacher et al., 1999). Over-irrigation with subsurface drip irrigation could result in massive deep drainage (Camp, 1998) and extended saturation of the rhizosphere leading to an hypoxic/anoxic root zone incapable of drawing water and nutrients especially in heavy clay soil (Bhattarai et al., 2006). The crop root system in subsurface drip irrigation is concentrated near to the emitter, and the release of irrigation water directly into the root zone improves plant access to water (Dippenaar et al., 1994) but sustained wetting fronts in the root zone, more prominent in heavy clay soil, expose the rhizosphere to hypoxia unless the irrigation rate is maintained below the level that creates saturation. Improvements of water use efficiency by subsurface drip irrigation and reduction of run-off and deep drainage, minimising environmental impact of irrigation, are achieved because of the ease for accurate control of irrigation rates and uniformity of application. However, the magnitude of the benefits depends on the crop, soil type, environment, system design, and intensity and frequency of irrigation (Ayars et al., 1999). These early studies on cotton irrigation focussed on off-farm movements of sediments and pesticides from cotton fields generally with furrow irrigation, however, the fate of fertilizer and pesticide movement under subsurface drip irrigation are very different to furrow irrigation. Subsurface drip irrigation on heavy clay soils that only wet-up soil beneath the surface can reduce the likelihood of off-site movement of water and sediments. Infiltration rates for vertisols are slower than on light and medium textured soils, and vertisols are prone to run-off, particularly if rain follows soon after surface irrigation. Comparisons of off-site movements for different subsurface drip irrigation rates could assist in optimising water use, minimising drainage and curtailing off-site movement of pollutants.

The main objective of this research was to determine the effects of different subsurface drip irrigation rates and furrow irrigation, based on the daily calculated evapo-transpiration rates of the crop, on the off-farm movements of suspended soils, nutrients and pesticides. Data on yield, water and radiation use efficiency and the physiological basis for the yield differences between furrow and subsurface drip irrigation treatments are separately published (Bhattarai et al., 2006).

## 2. MATERIALS AND METHODS

### 2.1. Site, climate, soil and crop details

Experiments were carried out for two consecutive years, 2001/02 and 2002/03, hereafter referred to as first year and second year, in the Emerald Irrigation Area, 148°19’49.8”E., 23°28’22.4”S., elevation 190 masl, in Central Queensland, Australia. The region is described as a semi-arid tropical environment, with summer-dominant rainfall, contributing two-thirds of yearly rainfall during the cotton season between October-March. The most erosive rainfall occurs in this region during the later part of the crop season and results in a high erosivity index (Carroll et al., 1995).

Rainfall in the first year was fairly well distributed with eight and three rain events exceeding 10 and 20 mm, whereas the second year was drier, with only one rain event with 10 mm. Most rain occurred in the months of Nov., Jan. and Feb. in the first year and Jan. and Feb. in the second year. Total rainfall during the crop period was 78 mm for the first year and 10 mm for the second year, very low compared to the annual mean of the previous 11 years (611 mm). The daily mean temperature and range was similar at c. 25.5 °C (range 18.6–33.9 °C) and 25.0 °C (range 17.5–33.3 °C) during the growing seasons. The average daily evaporation recorded was 8.5 mm (range 1.9–11.6) and 9.6 mm (range 3.2–13.9) with the mean seasonal relative humidity of 53 and 46% respectively, for first and second year. Likewise, the daily average solar radiation over the season was 24.8 (range 7.7–31.6), and 26.2 (range

9.2–32.1) MJ m$^{-2}$ and growing season totals were 3692 and 4324 MJ m$^{-2}$ for the first and second year, respectively.

The soil type was a hyperthermic gypsic vertisol, with 58% fine montmorillonitic and pH 7.8, and is designated as 6AUg-9 and 6AUg-12 under the Australian soil classification system (Northcote, 1971). The crop in the first year was sown with a tractor-driven seeder at 1 metre row spacing on low permanent 2 m wide beds on 26 September with cotton variety NuTopaz, Ingard$^{TM}$ and in the second year on 15 September with variety Sicot 289i. Crop establishment was 10–12 plants per metre row length as reported by Bhattarai et al. (2006).

### 2.2. Layout, experimental design and treatments

The experiments were laid out as randomised complete block design with three replications. Four daily irrigation treatments of 50, 75, 90, and 120% of crop evapotranspiration rate (approximately 6, 8, 10 and 12 mm d$^{-1}$) were applied to subsurface drip irrigation plots in the first year while in the second year 120% ETc was reduced to 105% ETc and peak daily applications were capped at 6, 8, 10 and 12 mm d$^{-1}$. The levels of irrigation were designed to provide differing levels of soil dryness, so that in-crop rainfall could be stored and rain-induced run-off limited, without compromising yield. The treatments 50% and 75% ETc are considered deficit irrigation treatments, since the amount of water supplied did not match that calculated to be necessary to satisfy the ETc. Plots were 0.4 ha in size, with drip lines 270 m in length. Three comparative furrow plots (530 m × 8 m), with similar soil and water quality, were located close to the sub-surface drip irrigation sites. Field capacity was at 43 mm $H_2O$ per 100 mm of soil depth, refill point at 32 mm and permanent wilting point at 22 mm per 100 mm soil depth. Details on field plot layout, design and treatments are presented in Bhattarai et al. (2006).

### 2.3. Irrigation, nutrition and crop management

Both subsurface and furrow irrigated crops were sown to a pre-irrigated full soil profile. An in-line water metre measured total applied water thereafter and the computerised controller monitored volumes applied daily to individual subsurface drip plots. Furrow plots were irrigated on seven and eight occasions in the first and second years. The furrow site was managed similarly to the subsurface drip plots except that for growth control with Pix® was used to reduce plant height in the furrow crop (Edmisten, 1994). The crop was fertilized with 250:25:60 kg NPK ha$^{-1}$. The whole amount of P and K was applied as basal dose to all treatments, whereas N application was split; 200 kg N ha$^{-1}$ was applied as pre-planting and the remainder was applied in 2 equally split applications from squaring to boll setting stage. The herbicides atrazine and diuron were not applied in either year; however, they had been used in earlier years. For example, in 2000/1, 3 kg ha$^{-1}$ atrazine 900 DF (90% active ingredient, a.i.) and 1.9 kg ha$^{-1}$ diuron 900 DF (90% a.i.) was applied to the soil for weed control. The crop in both years of the trial received 1.9 kg ha$^{-1}$ of fluometuron/prometryn mix (44% a.i.) as post-planting application, 2.3 L ha$^{-1}$ of trifluralin (48% a.i.) as pre-planting application and 2 kg ha$^{-1}$ of simazine (50% a.i.) as a pre-emergent application. The insecticide endosulphan 35 EC (emulsifiable concentrate, 35% a.i.) was applied as three applications of 3 L ha$^{-1}$ in the year prior to the experiment (2000/1). In the first and second years the crop received three applications of dimethoate 40 EC (40%, a.i.), each at 500 mL ha$^{-1}$ at 4 week intervals, to control aphids (*Aphis gossypii*) and two-spotted mites (*Tetranychus urticae*).

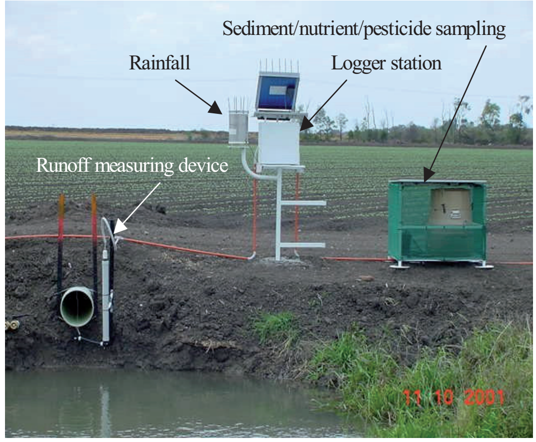


**Figure 1.** Monitoring station and 0.43 ha SDI bay discharge pipe instrumented to measure irrigation and rainfall run-off for sediment, nutrients and pesticides.

### 2.4. Operation, instrumentation and measurements of runoff

The details on instrumentation for weather monitoring, irrigation set up, soil moisture monitoring, and measurements of runoff are presented by Bhattarai et al. (2006). The schematic of instrumentation for bed load trap and discharge pipes for run-off measurements are presented in McHugh et al. (2003). Monitoring station and 0.42 ha subsurface drip irrigation bay discharge pipe instrumented to measure irrigation and rainfall induced run-off are shown in Figure 1.

### 2.5. Sample collection for suspended sediment load and water quality analysis

Water samples were collected by ISCO 3700 automated samplers when run-off discharged into stainless steel containers in either subsurface drip irrigation plots or furrow bay monitoring stations. Teflon sampling tubes and suction lines at the base of the container transferred the samples to the pumping sampler to minimise the chance of contamination. Each bay discharge pipe was fitted with copper tube splitters at the end of the pipe, with gravity feed into 10 L sample collection containers. Additional water quality samples were taken by hand when run-off occurred. Collected samples, within three hours of capture, were stored at 4 °C in a cool room before detailed analysis. The samples were analysed for concentration of sediments, nutrients such as N and P, the insecticides endosulfan and dimethoate, and the herbicides atrazin, diuron, fluometuron, simazin, trifluralin, and prometryn. No sampling of the bed load was undertaken.

Content of pollutants was calculated based on the concentrations and recorded run-off from the plots. N, P and all other pollutants were analysed following the methods by Water for Analytical Laboratory Use – Specification and Test Methods; (CEN EN ISO 3696: 1995) developed by International Organisation for Standardization USA, in an Australian accredited laboratory. The residual concentration of contaminants was compared to the ANZECC (2000) guidelines for fresh and marine water quality.

### 2.6. Data analysis

Data were subjected to analysis of variance following the general linear model. Means were compared using the least significant difference. All statistical determinations were made at $P \leq 0.05$. The crop, soil, water and pollutant data were subjected to analysis of variance to determine the effect of irrigation. The data were not subjected to a combined analysis over years, because the variety used in each year was different, and there was also a slight change in the treatment composition in second year, specifically the 120% ETc was changed to 105% ETc. All statistical analyses including correlations were computed using the statistical software Systat version 9.0 (SPSS Inc, 1999).

## 3. RESULTS AND DISCUSSION

### 3.1. Water input and soil moisture dynamics

The seasonal applied water in mm for each treatment is presented in Figure 2. Crop water uptake increased substantially after one month of seeding. In the first year the first irrigation was delayed in order to force deeper root penetration, but by doing so the crop was exposed to water stress at an early stage as seen in the comparison between Figures 2a and b, which impacted growth and yield in year one. Exposing plants to water stress slowed canopy cover in the early stage, and this can result in heavy run-off and erosion if unpredictable rain storms occur (Carroll et al., 1995).

Changes in soil water content after irrigation to 110 cm depth during the flowering period in the first year are presented in Figures 3. The soil water content measured below 60 cm after three hours of irrigation was saturated for 90 and 105% ETc subsurface drip and furrow irrigation, whereas 50 and 75% ETc recorded field capacity at 50–110 cm depth. Consequently furrow and subsurface drip at 120/105 and 90% ETc treatments incurred deep drainage in both years (Figs. 3) and also recorded soil moisture close to field capacity in the upper

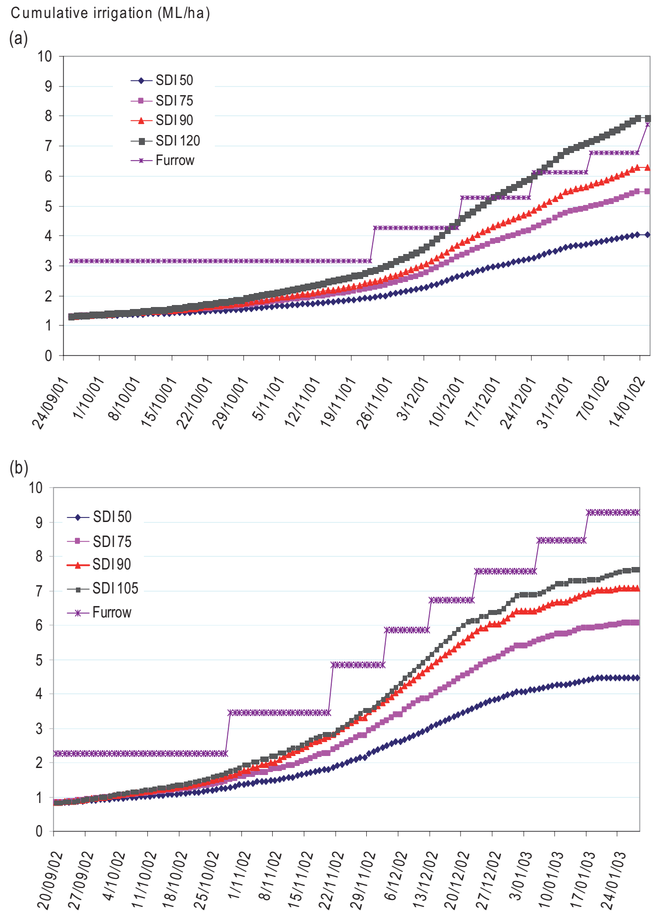


**Figure 2.** Cumulative applied water (ML ha$^{-1}$) over the crop period for different irrigation treatments in year one (top) and year two (bottom). SDI: subsurface drip irrigation rate in percentage of crop evapotranspiration rate (see Sect. 2.2).

surface, but the upper surface at 0–30 cm was drier for subsurface drip at 50 and 75% ETc. Subsurface drip treatments exhibited fairly stable soil water input based on crop daily evapotranspiration, whereas furrow plots showed peaks and troughs between irrigation events as it was time bound (Fig. 2). Therefore, the furrow crop was often exposed to water-logging for a few days after irrigation (Thongbai et al., 2001) and probable water stress before commencement of subsequent irrigations.

Unlike in furrow, the water movement in drip irrigation is described as three dimensional flow (Bresler, 1977) with the emitter placement at 40 cm depth. During redistribution time water that accumulates in the soil close to the drip source moves upward, downward and radially outward thereby extending the irrigation ‘bulb’ particularly in the higher irrigation rate. Fernandez-Galvez and Simmonds (2006) numerically measured and also modelled such three-dimensional flow of water with drip irrigation in both medium and heavy textured soils. Our data from vertisols are consistent with their measurements especially at higher subsurface drip irrigation rates. The subsurface drip at 50 and 75% ETc always had dry soil surface in the inter-rows. The top 30 cm soil in the inter-row spaces of those two treatments consistently maintained

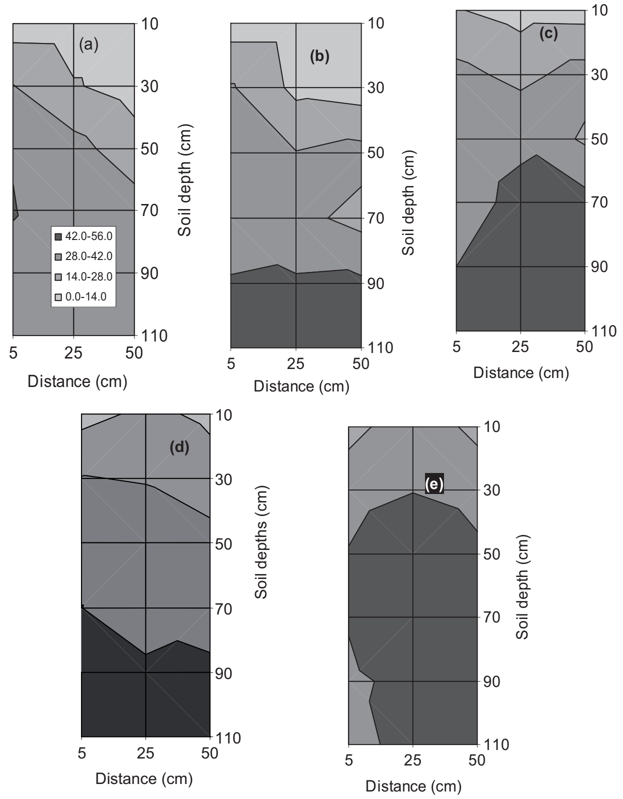


**Figure 3.** Soil moisture at different depths and lateral distances from the row at 74 days after seeding for different treatments (a: SDI50; b: SDI75; c: SDI90; d: SDI105 and e: FI) in the second year (measurements taken three hours after irrigation). Values are soil water depth mm 100 $mm^{-1}$ soil depth. SDI: subsurface drip irrigation rate in percentage of crop evapotranspiration rate (see Sect. 2.2). FI: furrow irrigation.

soil moisture less than refill point, i.e. 32 mm per 100 mm soil. This allowed for rapid infiltration and storage of rainfall and also reduced or eliminated run-off. With such dry soil surface conditions weed growth was not observed in the deficit subsurface drip treatments compared to higher drip irrigation rates and furrow. Despite rainfall storage advantage in the upper soil in drier treatments, these treatments had fewer roots there to capitalize quickly on additional rainwater (Bhattarai et al., 2006).

As a quantitative example of the capacity of drier treatments to absorb more rainfall, in the second year subsurface drip at 50 and 75% ETc received 36% and 14% less water than 90% ETc, and the profile in the latter was noted as almost full (Figs. 3). The lack of yield response to irrigation above 75% ETc suggests an oxygen limitation cause by hypoxia induced by the full rhizosphere (Bhattarai et al., 2006). A significant amount of run-off (64 mm) was noted in the wettest subsurface drip irrigation at 120% ETc in the first year but by reducing application to 105% ETc in the second year, run-off was halted in the wettest subsurface drip treatment. However, run-off was consistent from furrow irrigation in both years. Appropriately managed subsurface drip irrigation can completely contain run-off, unlike furrow irrigation. Subsurface drip irrigation supplying less than 100% ETc has capacity to capture rainfall soon after irrigation events, but for furrow rainfall that occurs immediately after irrigation is often lost, causing run-off from the field.

### 3.2. Sediment transport and soil erosion

Furrow irrigation in the first year led to significantly greater suspended soil loss of 5.97 t $ha^{-1}$ compared to 2.53 t $ha^{-1}$ with subsurface drip at 120% ETc but soil erosion was limited to furrow at only 4.56 t $ha^{-1}$ in the second year (Tab. I). Subsurface drip irrigation at 50, 75 and 90% ETc did not lead to soil erosion in either year. The results showed that subsurface drip irrigation rates which deliver water to cotton in excess of daily crop evapotranspiration demand can predispose a heavy clay soil to soil erosion. Rainfall was low for both years and run-off was limited to either tail water or post-irrigation rainfall from furrow irrigation in both years or to rainfall events for subsurface drip irrigation at 120, and 90% ETc in the first year only. Tail water is water that exits the cropping area as surface run-off during or after an irrigation event. When run-off was recorded from furrow irrigation, average sediment concentration was 4.2 and 5.2 g $L^{-1}$ for the first and second years. A significant polynomial regression between the applied irrigation water (X) and soil erosion (Y) was noted when only those treatments producing the erosion were considered [($Y = -4.3497X^2 + 176412X + 3568844$), ($r = 0.79$ [$P = 0.05$])].

In the first year there were seven run-off events for furrow irrigation and on each occasion the soil loss ranged from 0.03–2.62 t $ha^{-1}$, while in the second year run-off occurred in eight irrigation events and soil loss on each occasion ranged from 0.18–1.89 t $ha^{-1}$. Soil loss in both seasons from furrow was similar to that found in previous furrow irrigation studies on conventional cotton under dry conditions (Waters et al., 2000). Under dry weather conditions all soil was retained in subsurface drip irrigation treatments where irrigation levels were maintained at or below 75% of daily ETc. Generally soil loss for the highest subsurface drip rate resulted from a constant water outflow generated from saturated soil. This situation was rectified in the second season by reducing daily irrigation to 105% of ETc in the wettest treatment and was favoured by the increased evaporative demand in that season. In general, maintaining soil moisture in the upper soil below field capacity provided a considerable buffer to the effects of rainstorms. Consistent with our findings on the soil loss recorded on furrow plots, Carroll et al. (1995) studied soil erosion caused by rain and irrigation in cotton in the same area with respect to different furrow length in a vertisol and reported that total soil loss for the whole season due to rainfall and irrigation was approximately 4–5 t $ha^{-1}$. Rainstorms caused most of the seasonal soil loss in their study. However, in our study most of the soil loss was limited to irrigation events as the rainfall recorded in both seasons was very low compared to that of previous years. Carroll et al. (1997) also suggested that some run-off and soil erosion is ubiquitous for furrow irrigation in heavy clay soil, even in the absence of rainfall. Our experiments showed that run-off and soil erosion can also occur in subsurface drip irrigation

**Table I.** Effect of subsurface drip irrigation rates and furrow irrigation on cotton crop duration, canopy light interception, root dry weight and suspended soil loss (dry weight) in a vertisol at Emerald, Australia in 2001/02 and 2002/03. Deficit subsurface drip irrigation shortens the crop duration, and decreases light interception, root weight, and soil erosion. Value represents means for subsurface drip irrigation treatments, LSD and mean and SE (n = 3) for the furrow irrigation.

| Irrigation rate (% of [2]ETc) | First year (2001/2002) | | | | Second year (2002/2003) | | | |
|---|---|---|---|---|---|---|---|---|
| | Harvest (days) | LI[1] (%) | Root (g plant$^{-1}$) | Erosion (t ha$^{-1}$) | Harvest (days) | LI (%) LI (%) | Root (g plant$^{-1}$ ) | Erosion (t ha$^{-1}$) |
| SDI50[3] | 119 | 74 | 21.2 | 0.00 | 138 | 64 | 21.4 | 0.00 |
| SDI75[4] | 133 | 79 | 23.2 | 0.00 | 146 | 68 | 20.3 | 0.00 |
| SDI90[5] | 140 | 80 | 23.3 | 0.01 | 151 | 74 | 22.3 | 0.00 |
| SDI120/105[6] | 148 | 86 | 23.6 | 2.53 | 149 | 72 | 23.9 | 0.00 |
| *LSD*[7] (6 df) | 0.46 | 1.4 | 2.8 | 0.08 | 3.09 | 2.5 | 2.1 | 0.00 |
| FI[8] | 143 | 90 | 20.4 | 5.97 | 152 | 75 | 19.4 | 4.56 |
| *SE*[9] (n=3) | 0.49 | 2.7 | 3.9 | 0.058 | 2.1 | 3.1 | 2.9 | 0.064 |

[1] LI: Light interception;
[2] ETc: Evapo-transpiration rate of the crop;
[3] SDI50: Subsurface drip irrigation at 50% of daily ETc;
[4] SDI75: Subsurface drip irrigation at 75% of daily ETc;
[5] SDI90: Subsurface drip irrigation at 90% of daily ETc;
[6] SDI120: Subsurface drip irrigation at 120% of daily ETc; (105% in second year);
[7] LSD: Least significant difference for SDI treatments;
[8] FI: Furrow irrigation;
[9] SE: Standard error.

cropping when the irrigation rate greatly exceeds the daily crop evaporative demand. Water applied at 105% of ETc or lower did not lead to soil loss in the current experiment; however, the rainfall was quite low in both trial seasons. As long as rainfall intensity is less that the soil infiltration rate keeping a dry soil surface with deficit irrigation, i.e. irrigation rate less than 90% of ETc, should allow quick infiltration of rain and should not lead to run-off. Phene et al. (1991) and Camp et al. (1999) also reported the ability of subsurface drip irrigation to control run-off and erosion in different soil types, as evidenced in our experiments in both years.

The irrigation-induced soil erosion was the dominant cause for the major soil loss in both years particularly for furrow irrigation. However, unexpected heavy rainstorms after irrigation and before the uptake of irrigation water by the crop can have a significant impact, aggravating the soil erosion particularly in a furrow-irrigated crop. The crop canopy cover could play an important conditioning role in limiting the intensity of rainfall-induced soil erosion. Carroll et al. (1995) in a vertisol showed a strong negative correlation between crop canopy cover during rain and soil erosion in both short and long furrow length cotton crops. However, in our study the crop canopy cover estimated by light interception (Tab. I) did not show a strong relationship with run-off because both years were relatively dry. Runoff from the subsurface drip treatment in most cases was associated with rainfall events; a significant (r = 0.75) exponential function $y = 898.16e^{0.1282x}$ between rainfall amount (X) and run-off from the field (Y) was noted. In the Emerald Irrigation Area tail water is reticulated on-farm and all farms have the capacity to retain about 25 mm of a single-event run-off. However, our data showed that considerable amounts of sediment were removed in run-off. The intensity of run-off and soil erosion associated with furrow increases where tail water recirculating facilities do not exist. The soil erosion in both years was largely irrigation induced. Furrow irrigation significantly increased suspended soil loss (5.26 t ha$^{-1}$) compared to subsurface drip irrigation at 120% of ETc (2.53 t ha$^{-1}$) whereas no erosion was recorded with deficit subsurface drip irrigation treatments.

### 3.3. Off-site nutrient movements and transport

#### *3.3.1. Nitrogen*

Nitrogen removal by run-off was significantly greater in furrow compared to wetter subsurface drip irrigation at 120/105% ETc, and did not occur in deficit irrigation at 50 and 75% ETc in either year. Subsurface drip at 90% ETc recorded a small amount of nitrogen removal (0.31 kg ha$^{-1}$) in the first, but not in the second, year (Tab. II). The nitrogen loss in both years was largely associated with irrigation events (Figs. 4, 5). The first five of seven furrow irrigation events in the first year accounted for the loss of c. 18 kg ha$^{-1}$ of the pre-applied nitrogen; later irrigation events did not contribute more. The highest individual amount of N lost from the field in the first year coincided with inter-row cultivation in August, and at 37.6 mg L$^{-1}$ (Fig. 4) was 50 times greater than the ANZECC (2000) threshold value of 0.75 mg L$^{-1}$. In the second year, the offsite nitrogen movement by furrow reduced to 11.32 kg ha$^{-1}$ (± 1.28 kg ha$^{-1}$) due to lower rainfall and optimisation of the furrow irrigation. Small quantities of nitrogen loss of 0.38 ± 0.02 kg ha$^{-1}$ were also recorded from the subsurface drip at 105% ETc, as this treatment had a wet upper soil profile. Irrigation was in excess of crop transpiration in this treatment and

**Table II.** Effect of subsurface drip irrigation rates and furrow irrigation on total pollutant load, and mean concentration and range for run-off samples collected from irrigation treatments in a vertisol at Emerald in 2001/02 and 2002/03. Deficit subsurface drip irrigation reduces the soil loss and off-farm movements of nitrogen, phosphorus, herbicides and insecticides.

| Pollutants[5] | First year (2001/2002) | | | | | Second year (2002/2003) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | SDI[1] 50 | SDI[2] 75 | SDI[3] 90 | SDI[4] 120 | Furrow | SDI[1] 50 | SDI[2] 75 | SDI[3] 90 | SDI[4] 105 | Furrow |
| Nitrogen (kg ha$^{-1}$) | – | – | 0.31 | 2.88 | 18.80 | – | – | – | 0.38 | 11.32 |
| Concentration[5] | – | – | 7.96 | 13.86 | 14.23 | – | – | – | 19.76 | 7.42 |
| Range[6] | – | – | 6.75–9.46 | 4.73–22.15 | 2.3–37.57 | – | – | – | 17.83–22.61 | 0.92–22.94 |
| Phosphorus (g ha$^{-1}$) | – | – | 46.08 | 37.54 | 353.61 | – | – | – | 0.59 | 1202.37 |
| Concentration[5] | – | – | 1.30 | 0.29 | 0.31 | – | – | – | 0.27 | 0.41 |
| Range[6] | – | – | 1.01–1.53 | 0.14–0.53 | 0.29–0.33 | – | – | – | 0.01–0.38 | 0.18–1.04 |
| Atrazine (g ha$^{-1}$) | – | – | 1.72 | 4.56 | 107.86 | – | – | – | – | 130.88 |
| Concentration[7] | – | – | 0.03 | 0.08 | 0.07 | – | – | – | – | 0.08 |
| Range[8] | – | – | 0.03–0.04 | 0.05–0.10 | 0.03–0.11 | – | – | – | – | 0.01–0.15 |
| Diuron (g ha$^{-1}$) | – | – | 4.08 | 193.76 | 508.27 | – | – | – | – | 239.55 |
| Concentration[7] | – | – | 0.13 | 2.89 | 0.40 | – | – | – | – | 0.41 |
| Range[8] | – | – | 0.09–0.18 | 0.04–9.68 | 0.21–0.67 | – | – | – | – | 0–0.55 |
| Fluometuron (g ha$^{-1}$) | – | – | 84.36 | 271.47 | 1152.06 | – | – | – | – | 814.53 |
| Concentration[7] | – | – | 1.81 | 13.36 | 1.49 | – | – | – | – | 2.12 |
| Range[8] | – | – | 1.66–1.96 | 5.82–23.6 | 0.17–4.2 | – | – | – | – | 0.12–4.12 |
| Prometryn (g ha$^{-1}$) | – | – | 365.73 | 103.41 | 62.62 | – | – | – | – | 490.21 |
| Concentration[7] | – | – | 4.60 | 0.64 | 0.12 | – | – | – | – | 0.92 |
| Range[8] | – | – | 0.52–8.73 | 0.11–1.0 | 0.04–0.22 | – | – | – | – | 0.7–1.87 |
| Trifluralin (g ha$^{-1}$) | – | – | – | – | 286.39 | – | – | – | – | – |
| Concentration[7] | – | – | – | – | 6.21 | – | – | – | – | – |
| Range[8] | – | – | – | – | 0.90–9.63 | – | – | – | – | – |
| Simazine (g ha$^{-1}$) | – | – | – | – | – | – | – | – | – | 12.99 |
| Concentration[7] | – | – | – | – | – | – | – | – | – | 0.004 |
| Range[8] | – | – | – | – | – | – | – | – | – | 0–0.03 |
| Dimethoate (g ha$^{-1}$) | – | – | 0.76 | 325.88 | 350.98 | – | – | – | – | – |
| Concentration[7] | – | – | 0.60 | 3.51 | 1.22 | – | – | – | – | – |
| Range[8] | – | – | 0.60–0.60 | 2.2–4.82 | 0.4–2.03 | – | – | – | – | – |
| Endosulphan (g ha$^{-1}$) | – | – | 0.81 | 112.65 | 289.50 | – | – | – | – | – |
| Concentration[7] | – | – | 0.64 | 0.70 | 0.37 | – | – | – | – | – |
| Range[8] | – | – | 0.64–0.64 | 0.50–0.90 | 0.15–0.64 | – | – | – | – | – |

[1] SDI50: Subsurface drip irrigation at 50% of daily ETc;
[2] SDI75: Subsurface drip irrigation at 75% of daily ETc;
[3] SDI90: Subsurface drip irrigation at 90% of daily ETc;
[4] SDI120: Subsurface drip irrigation at 120% of daily ETc, (105% in second year);
[5] Concentration: mg L$^{-1}$;
[6] Range: mg L$^{-1}$;
[7] Concentration: μg L$^{-1}$;
[8] Range: μg L$^{-1}$.

was thus pre-disposed to run-off after some rainfall events. The frequency of run-off and total nitrogen removal was greater with furrow irrigation, however, the minimum concentration of nitrogen in the run-off on some occasions was higher in the wetter subsurface drip irrigation treatments than furrow irrigation (Tab. II). Nitrogen run-off, especially in furrow irrigation, was consistent with run-off values of 18.8 kg ha$^{-1}$ recorded on flooded paddy by Yoshinaga et al. (2007). Results of Shock (2005) for cotton on a sandy loam also suggested that although the total nitrogen loss on subsurface drip irrigation was lesser than furrow, the nitrogen concentration of the run-off was greater for some events in subsurface drip irrigation. Total amounts of nitrogen loss were closely related to the quantity of runoff from each treatment.

### 3.3.2. *Phosphorus*

The total phosphorus load in the run-off for the entire season was significantly greater for furrow at c. 354 g ha$^{-1}$ in the first year and 1202 g ha$^{-1}$ in the second year compared to subsurface drip irrigation (Tab. II). Subsurface drip at 90 and 120% ETc recorded total phosphorus losses of 46 and 38 g ha$^{-1}$ respectively in the first year (Fig. 5), whereas in the second year movement of phosphorus in the run-off water was reduced to 0.6 g ha$^{-1}$ and only in 105% ETc; no phosphorus run-off was detected in any other deficit subsurface drip irrigation treatment. The phosphorus concentrations in the run-off were higher in furrow than subsurface drip at 120% ETc, but 90% ETc had a higher concentration of phosphorus in the

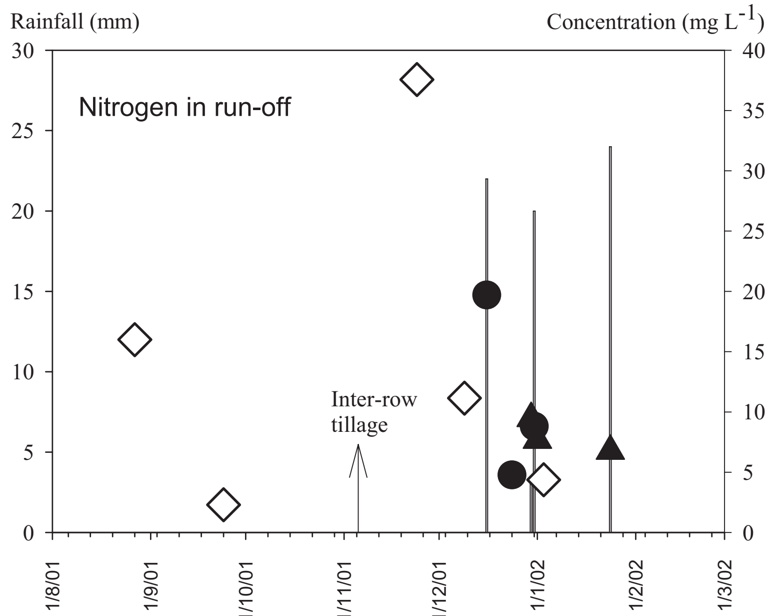


**Figure 4.** Nitrogen concentration in the different run-off events after irrigation and/or rainfall for cotton in the first year (2001/2002). Legend: ◇ = Furrow Irrigation; ● = Subsurface Drip Irrigation at 120% ETc; ▲ = Subsurface Drip Irrigation at 90% ETc.

run-off water than did either 120% ETc or furrow. The concentration of phosphorus in the run-off water was above the ANZECC (2000) threshold level for fresh water (0.01 mg $L^{-1}$) irrespective of irrigation treatments. Total phosphorus movement was similar to that of nitrogen in that considerable losses occurred from furrow for the majority of the irrigation events. But in contrast to total nitrogen, no phosphorus was detected in the first runoff in the first year and its load increased with each event to as much as 160 g $ha^{-1}$ (Fig. 5) from a total of 25 kg $ha^{-1}$ phosphorus applied to the crop. In both years, furrow lost greater amounts of phosphorus through runoff associated with irrigation, especially after tillage events. The work by Westermann et al. (2001) highlighted the magnitude of the off-farm movements of phosphorus in irrigation run-off. They concluded that the average total phosphorus concentration in run-off was not related to the soil phosphorus test, but was linearly related to sediment concentration. These authors noted phosphorus concentration in run-off of 1.08 mg $L^{-1}$ in a silty loam with furrow irrigation, whereas we observed a lower concentration (0.31–0.41 mg $L^{-1}$) in heavy clay soil with furrow and in the wettest subsurface drip irrigation treatments, but a higher concentration in the 90% ETc treatment at 1.30 mg $L^{-1}$ (range 1.01–1.53 mg $L^{-1}$).

Total phosphorus losses in runoff from agricultural fields are generally not large; however, concentrations that cause eutrophication can be as low as 0.02 mg $L^{-1}$ (UNEPA, 1996). At times the total phosphorus concentration in the run-off samples from our experiments exceeded UNEPA threshold values. Generally inorganic phosphorus concentration of 0.2–0.3 mg $L^{-1}$ is required in the soil solution for normal plant growth (Barber, 1995). Since this minimum concentration is ten times more concentrated than the EPA value that can cause eutrophication, essentially phosphorus runoff from the crop fields must be halted. Subsurface drip irrigation at 75% ETc obviated phosphorus movement. Sediments eroded from irrigated agricultural soils typically could contain 900–1200 mg $kg^{-1}$ of total phosphorus (Westermann et al., 2001). However, the early work by Carter et al. (1974) reported that the clay particles may contain as much as 1400 mg $kg^{-1}$ total phosphorus in the sediment. In large scale field trials, the median seasonal total phosphorus loss from 32 surface-irrigated agricultural fields was 4.9 kg $ha^{-1}$ and depended on the amount of sediment eroded (Berg and Carter, 1980). Furthermore, Berg and Carter (1980) recorded a median soluble phosphorus removal of 0.15 kg $ha^{-1}$ which comprised only 3% removal of the total phosphorus, whereas our data showed that the P removal from subsurface drip at 90 and 105/120 ETc was negligible (0.1%) but furrow recorded a significantly greater amount (3.1%) of the applied phosphorus. Our study also noted a relatively low maximum phosphorus load in the runoff at 1.2 kg $ha^{-1}$ for furrow and removal of only a very small quantity (38–46 g $ha^{-1}$) for the wetter subsurface drip irrigation treatments.

### 3.4. Herbicide transport

#### *3.4.1. Atrazine and diuron*

A pre-emergence application of 3 kg $ha^{-1}$ atrazine (90% a.i.) was applied to a cotton crop in 2000/01, the year before our first year experiment. A small amount of residual atrazine, 1.7 and 4.6 g $ha^{-1}$, was recorded in run-off in the wetter subsurface drip treatments in 90 and 120% ETc in the first year only whereas substantial amounts (108 and 131 g $ha^{-1}$) were evident from furrow irrigated plots in both years (Tab. II and Fig. 5). This was not due to a greater herbicide concentration

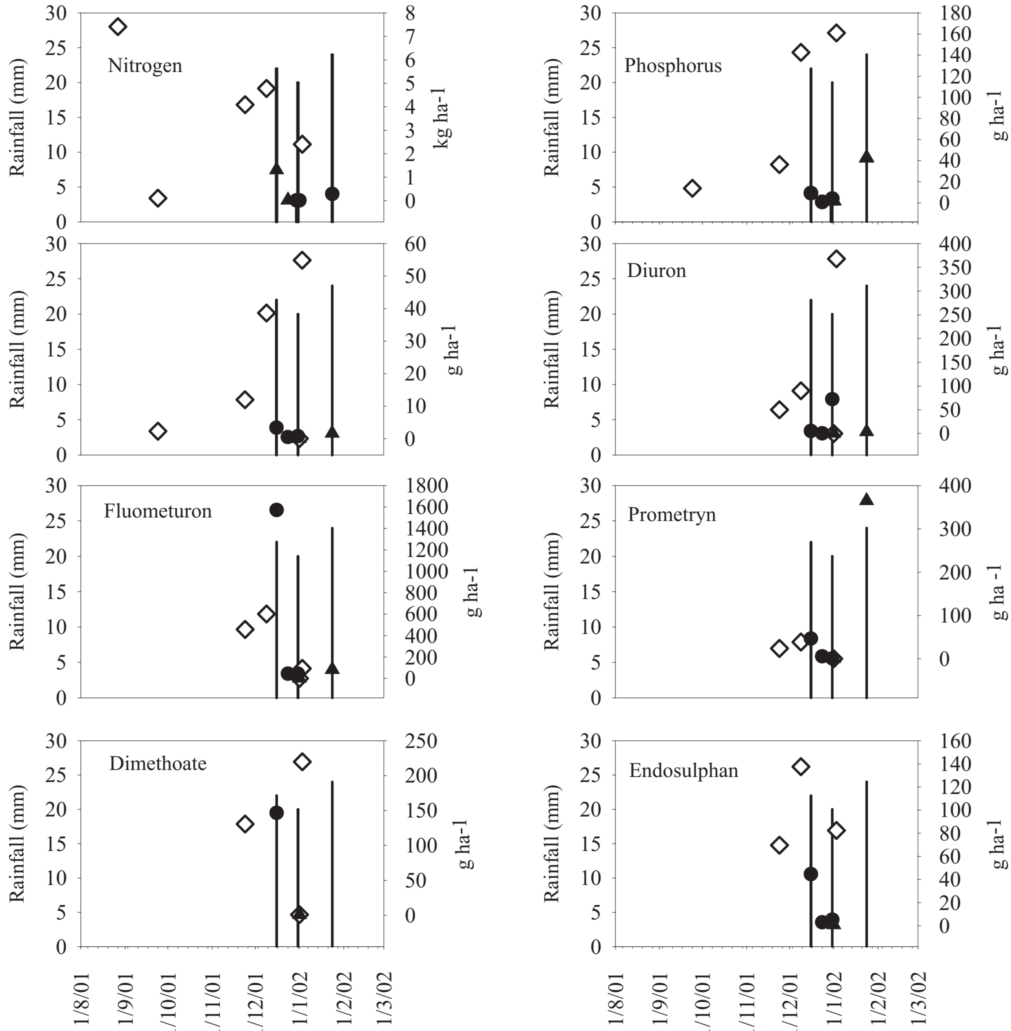


**Figure 5.** Total quantities of nutrients and pesticides in the runoff samples collected from each rainfall and irrigation event for furrow and subsurface irrigated sites in the first year (2001/2002). Dates are expressed in dd/mm/yy. Legend: ◇ = Furrow Irrigation, ● = Subsurface Drip Irrigation at 120% ETc, ▲ = Subsurface Drip Irrigation at 90% ETc.

(Tab. II), but due to more run-off from the furrow compared to the subsurface drip irrigation. The amount of atrazine off-site movement in general was associated with the quantity of run-off, except after tillage in early November 2001 (Fig. 5), when the post-tillage concentration in the runoff increased sharply to 0.11 $\mu g\,L^{-1}$. Previous work by Behki and Khan (2001) also suggested a significant contribution to the off-site movement of atrazine from previous season applications (as much as 45–53% atrazine was bound to soil in the year of application). The average concentrations of atrazine in the run-off were consistent in furrow irrigation (0.07–0.08 $\mu g\,L^{-1}$) over the two years, suggesting that the tillage in the current season and between seasons exposed the residual atrazine (Gaynor et al., 2002) which was then transported with the run-off following the furrow irrigation.

As for atrazine, no diuron was applied in current seasons, but was detected in both years in the furrow run-off, as 1.9 $kg\,ha^{-1}$ of diuron (90% a.i.) was applied to the plot in the previous season (2000/01). Total diuron run-off in furrow (508.3 $g\,ha^{-1}$) exceeded subsurface 120 (193.7 $g\,ha^{-1}$) and 90% ETc (4.1 $g\,ha^{-1}$) in the first year whereas total diuron run-off in furrow was much less in the second year (239.5 $g\,ha^{-1}$), and none was detected from subsurface drip irrigation plots (Fig. 5). Diuron concentration in the run-off for 120% ETc was 20 and 7 times greater than that of 90% ETc and furrow irrigation, respectively (Tab. II) in the first year. Diuron has a soil half life of more than 90 days, high soil sorption, moderate adsorption to soil (Tab. III), and it is easily redistributed in soil with tillage (Spalding et al., 2003), hence, its substantial residue was still detected in the soil surface two years after application.

Atrazine concentration in the run-off did not exceed the ANZECC (2000) trigger for 99 and 80% protection, respectively (Tabs. II, III). However, for diuron all of the run-off events exceeded the concentration for 99% species protection but were well under for the 80% species protection. Of

**Table III.** Chemistry of pollutants (soil sorption index, water solubility, soil half life), physical characteristics (surface run-off, leaching, adsorption run-off potentials), toxicity (toxic to fish, toxic to birds and other wildlife) and trigger value at alternative level of protection (99 and 80 percent species protection) according to ANZECC 2000 guidelines for fresh water.

| Common name | Soil sorption index ($K_{oc}$) | Water solubility (ppm) | Soil half life (days) | Surface run-off | Leaching | Adsorption run-off potential | Trigger value (μ g $L^{-1}$) 19% | Trigger value (μ g $L^{-1}$) 80% | Toxic to fish | Toxic to birds and other wildlife |
|---|---|---|---|---|---|---|---|---|---|---|
| Atrazine | 100 | 33 | 60 | L | L | M | 0.7 | 150 | S | PN |
| Fluometuron | 100 | 105 | 85 | L | S | M | ID | ID | S | PNT |
| Prometryn | 400 | 33 | 60 | L | M | M | ID | ID | M | PNT |
| Diuron | 480 | 42 | 90 | L | M | M | 0.02 | 160 | M | S |
| Trifluralin | 8000 | 8.3 | 60 | M | S | L | 2.6 | 9.0 | VH | PNT |
| Simazine | 130 | 6.2 | 60 | L | L | M | 0.2 | 35 | S, PNT | PNT |
| Dimethoate | 20 | 39800 | 7 | S | M | M | 0.10 | 0.30 | M | M |
| Endosulphan | 12400 | 0.32 | 50 | M | VS | L | 0.03 | 1.80 | VH | H-M |

(Source: Ferruzi and Gan, 2004)

ARP: Adsorption run-off potential; L: Large; S: Small; M: Medium; VS: Very Small; VH: Very high; PNT: Potentially non toxic.

particular interest was the much higher concentrations of diuron in the wettest SDI treatment than the furrow irrigation in the first year.

### 3.4.2. *Fluometuron and prometryn*

All plots received a fluometuron + prometryn mix (50% each) at 1.9 kg ha$^{-1}$ (44% a.i.) as a post-planting application in both years. The movement of both herbicides was detected in furrow run-off in both years, whereas in subsurface drip at 90 and 120% ETc they were detected only in the first year (Fig. 5). In the first year fluometuron concentration was, as for atrazine, greatest in subsurface drip irrigation at 120% ETc compared to both 90% ETc and furrow (Tab. II). Removal of fluometuron in runoff was recorded at 84 g ha$^{-1}$ for 90%, compared to 271.5 g ha$^{-1}$ for 120% ETc and 1152 g ha$^{-1}$ for furrow in the first year. In the second year, furrow resulted in a total transport of 814.5 g ha$^{-1}$ (Tab. II). Consistent with our results, fluometuron has been frequently detected in Australian cotton runoff by Rose et al. (2006) and in watersheds of south eastern USA where cotton is widespread (Coupe et al., 1998; Thurman et al., 2000). The ANZECC guidelines' trigger value for fresh water ecosystem is not well established for fluometuron but concentrations as high as 24 μg L$^{-1}$ in some of the run-off events exceed EU directives on minimum threshold limits for aquatic organisms (Eignor and Abdel-Saheb, 2005).

The total prometryn in run-off was greatest in subsurface drip at 90 ETc (365.7 g ha$^{-1}$), followed by 120% ETc (103.4 g ha$^{-1}$) and furrow (62.6 g ha$^{-1}$) in the first year, but was limited to furrow only (490.2 g ha$^{-1}$) in the second year. Average concentrations of prometryn in run-off were greatest for 90% ETc followed by 120% ETc and least for furrow in the first year (Tab. II). Prometryn has lower solubility (33 vs. 105 ppm) and a higher soil sorption index (400 vs. 100 Koc) compared to fluometuron (Tab. III), therefore it is more labile and the residue can remain in the soil for a longer period. That may have contributed to the higher prometryn run-off from furrow in the second year. In spite of lower runoff from subsurface 90 and 120% ETc compared to furrow, greater prometryn movement was primarily caused by higher concentration in the runoff associated with the drip irrigation treatments. Silburn and Glanville (2002) showed that the transport of prometryn was largely in the water phase rather than in sediments from a cotton field. As the run-off from the subsurface drip irrigation contained less suspended sediment but more concentrated water than the furrow plots in our trial, it resulted in a greater amount of prometryn movement from the subsurface drip irrigation than furrow treatments. Our data suggest that concentration of prometryn in run-off was not correlated with concentration of sediment in run-off ($r^2$ = 0.027). The ANZECC guideline values for fresh water ecosystem is not well established for prometryn, but concentrations as high as 4.6 μg L$^{-1}$ were recorded in some run-off events. For both fluometuron and prometryn, concentrations in runoff were greater in drip than furrow irrigation treatments.

### 3.4.3. *Trifluralin and simazine*

Pre-planting application of trifluralin 2.3 kg ha$^{-1}$ (48% a.i.) was only made in the first year and resulted in movement only in the furrow irrigation during that year. Simazine at 2 kg ha$^{-1}$ (50% a.i.) as a pre-planting application was applied only in the second year and its movement was limited solely to furrow irrigation. The furrow runoff carried more than 10% of the applied trifluralin which contrasts with data of Leonard et al. (1979) that showed only a small proportion of the applied trifluralin in run-off. Total trifluralin loss in run-off was strongly related to run-off volume rather than to concentrations in that run-off because the soil sorption index for trifluralin is very high (8000 Koc) (Silburn and Glanville, 2002). Trifluralin movement in the runoff has been reported to vary greatly due to sediment load, sediment type, formulation used, amount and duration of irrigation and canopy cover than solely on the method of irrigation (Wauchope, 1978). The concentrations in the runoff ranged from 0.9–9.63 μg L$^{-1}$ (Tab. II), and at times was greater than 2 μg L$^{-1}$, the US Environmental Protection Agency advisory level for trifluralin in drinking water (Tab. III). The average concentration of trifluralin in run-off water was 6.2 μg L$^{-1}$ and a total of 286 g ha$^{-1}$ trifluralin run-off was recorded over the crop season.

The total simazine mass recovered in the run-off water from the furrow treatment was 12.99 g ha$^{-1}$ and its concentrations in irrigation run-off averaged 0.004 μg L$^{-1}$ and ranged from 0–0.03 μg L$^{-1}$ (Tab. II), well below the ANZECC (2000) trigger value for 99% species protection. Simazine concentration decreased in run-off with increasing irrigation rates/run-off volume (Tab. II). Our results contrast with the findings of Liu and O'Connell (2002) where off-site movement of simazine was greater in non-irrigated plots (concentrated in the soil solution) compared to regularly irrigated plots (low concentration in the soil solution) in response to 35 mm simulated rain in a citrus orchard.

### 3.5. Insecticide transport

#### *3.5.1. Dimethoate*

Three applications of dimethoate in the first year at four week intervals and one application in the second year, all at the rate of 500 mL ha$^{-1}$ (40% a.i.) , were sprayed to control aphids and spider mites. Off-site dimethoate movement was noted in the first year only (Fig. 5). Furrow irrigation recorded highest losses (351 g ha$^{-1}$) followed by subsurface drip irrigation at 120% ETc (325 g ha$^{-1}$), and a very small amount at 90% ETc (0.8 g ha$^{-1}$), and none in 50 and 75% ETc. Similarly, average dimethoate concentration in run-off was highest (3.5 μg L$^{-1}$, range 2.2–4.8) in subsurface drip irrigation at 120% ETc followed by furrow (1.2 μg L$^{-1}$, range 0.4–2.0), and least for subsurface at 90% ETc (0.6 μg L$^{-1}$) (Tab. II). Dimethoate concentrations in all run-off events were well above trigger values (Tabs. II, III). The dimethoate run-off from subsurface drip plots was largely associated with rainfall events, whereas in furrow it was associated with both rain and irrigation events. As might be expected, soil management practices that increase water holding capacity of the soil and minimize erosion have been shown to be effective in minimizing off-farm dimethoate movement. For example, Antonious et al. (2007) evaluated the dimethoate residues collected from broccoli field run-off under three soil management practices and showed that mulching with sewage sludge significantly reduced off-site movement (151 mg ha$^{-1}$) compared to mulching with yard compost (377 mg ha$^{-1}$) and without mulching (724 mg ha$^{-1}$) in a silty loam soil.

#### *3.5.2. Endosulphan*

Endosulphan was not applied at all in the experimental years, but had been applied at the rate of 3 L ha$^{-1}$ (35% a.i.) in the previous season (2000/2001). Substantial off-site movement of endosulphan was noted in the first year for furrow irrigation (289 g ha$^{-1}$), followed by subsurface drip at 120% ETc (113 g ha$^{-1}$) and also trace amounts in 90% ETc (1 g ha$^{-1}$) (Tab. II). No endosulphan traces in the run-off were recovered in the second year trial. The off-site endosulphan movement for subsurface drip treatments was largely associated with subsequent rainfall events, whereas for furrow it was associated with irrigation and rainfall (Fig. 5). In current management systems, fields are often left bare in the early stages of a cotton crop and endosulphan is sprayed directly onto the soil between plants. With surface irrigation and/or rainfall part of this applied endosulphan infiltrates into the soil (Connolly et al., 2001). The infiltrated endosulphan was most likely brought to the surface by tillage in the following cropping season and subjected to run-off as observed in this experiment. All of the run-off events (concentrations ranging from 0.15–0.90 μg L$^{-1}$) exceeded the endosulphan concentration for 99% species protection, but rarely exceeded that for 80% species protection (Tabs. II, III).

In general fertilizers and pesticides meet a variety of fates after application. They may volatilise, break down in sunlight, or be carried away by runoff water before reaching their targets. After reaching the soil they may be taken up by plants, adsorbed to soil particles, broken down by soil microorganisms, or be moved off-target to water sources. The fate of pesticides in the environment depends upon a number of factors including soil characteristics, site features, pesticide properties and pesticide use practice. Our data suggest that subsurface drip irrigation can be an effective component of best management practices for cotton for containing most of these pollutants when the irrigation rates are maintained at less than the potential evapotranspiration rate. A subsurface drip irrigation system managed under deficit irrigation has the potential to store in-crop rainfall and could have considerable advantage over wetter subsurface drip and furrow irrigation in terms of reduction of the environmental impacts of agrochemical runoff under rainstorm conditions. Nevertheless, when off-farm movement of pollutants was recorded with wet subsurface drip irrigation, in run-off promoted by rainfall, the concentrations of these pollutants were found to be greater than those from conventional furrow irrigation and well above the ANZECC (2000) threshold levels. Such higher concentrations must be contained on the farm by growers otherwise they pose serious threats to downstream water bodies that are contaminated with such run-off. In spite of the generally higher concentration of pesticides and N and P in runoff from wetter subsurface drip irrigation than from furrow irrigation, the total amount removed from fields was greater in the latter.

## 4. SUMMARY AND CONCLUSION

Furrow irrigation doubled suspended soil loss compared to subsurface drip at 120/105% ETc. Off-farm movement of nitrogen was significantly greater for furrow and the wettest subsurface drip irrigation at 15.1 and 2.9 kg ha$^{-1}$, respectively and phosphorus at 778 g ha$^{-1}$ was limited to furrow irrigation. Deficit subsurface drip irrigation treatments prevented nitrogen and phosphorus removal in both years. Herbicides such as atrazine and diuron, which were applied in prior seasons, were recovered in run-off from furrow and subsurface drip at 120% ETc at amounts up to 27% of that applied. Significant amounts of in-crop applied fluometuron (4–61% of that applied) and prometryn (3–26% of that applied), were detected in the run-off from wetter subsurface drip (90 and 120% ETc) and furrow irrigation. Trifluralin (12% of that applied) and simazine (0.6%) movement was limited to furrow and restricted to the season of application only. The insecticide endosulphan was applied only in the season prior to the first year, but as much as 4–10% of its applied amount was recorded in the runoff in the first year in furrow irrigation. Likewise, 23–27% of the current application of dimethoate was recorded in the runoff from subsurface drip at 120% ETc and furrow and increased with higher application rate. Although the quantity of off-farm movement of pollutants was reduced with subsurface drip irrigation, on occasions their concentrations in the run-off exceeded ANZECC (2000) guideline trigger values for protection of 99% of target species. Therefore, unless deficit irrigation is practised, complete containment of run-off is important if one is to minimize the impact of off-farm movement of pollutants with subsurface drip irrigation. Furrow and wetter subsurface drip irrigation rates at 105 and 120% ETc not only led to large amounts of suspended soil in run-off and to off-farm movements of fertilizers and pesticides, but also resulted in lower water use efficiency (Bhattarai et al., 2006). Considerable water saving and reduction of off-site movement of pollutants is achievable with appropriately-managed deficit subsurface drip irrigation at 75% ETc. Objectively-managed subsurface drip irrigation could help achieve economic and environmental goals by producing comparable yield to furrow irrigation coupled with increased water use efficiency, and by minimising off-site movement of pollutants at the farm scale.

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