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Reduction of shoot fly damage in irrigated post-rainy season sorghum by manipulating irrigation

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Summary

Soil moisture was manipulated in an attempt to control shoot fly (*Atherigona soccata* Rondani) incidence in irrigated post-rainy season sorghum grown under a rainout shelter (ROS) and in field conditions. After uniform irrigation at sowing, the plants were subjected to water stress at young seedling stage (7–28 days after emergence, DAE) for different lengths of time. Soil water had profound effects on the production of water droplets on the surface of the central whorl leaf of seedlings (leaf surface wetness, LSW) of sorghum genotypes. LSW, which facilitates movement of the larvae, was more drastically affected in susceptible (CSH 5) than in moderately resistant (IS 1054) sorghum genotypes.

Shoot fly oviposition (infestation) and deadhearts (crop damage) were much higher in treatments with full irrigation (control) than in treatments to which less water was applied during the first 3 wk after seedling emergence. This resulted in higher plant biomass and overall grain yield in the latter treatments than in the control. Using insecticides to control shoot fly infestation, it was shown that a simple cultural practice of inducing plant stress by reduced soil moisture content during early plant growth gave the same or better control of shoot fly damage and the same or higher grain yield than insecticide-protected plots with full irrigation. Thus the costs associated with irrigation requirement and insecticide can be greatly reduced in the former management option compared with the latter. It is suggested that manipulation of soil water content during the vulnerable early stages of crop growth can reduce shoot fly damage in irrigated post-rainy season sorghum.

Key words: Shoot fly, *Atherigona soccata*, Diptera, Muscidae, deadheart, sorghum, LSW, control by plant stress, insecticide

Introduction

Sorghum, *Sorghum bicolor* (L.) Moench is a major source of food for millions of people living in the semi-arid tropics of Africa and Asia and shoot fly (*Atherigona soccata* Rondani) (Diptera: Muscidae) is one of the major factors limiting its production. Shoot fly larvae feed on the growing point of young seedlings (7–28 days after emergence, DAE) and cause crop damage (deadheart).

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In India, post-rainy season sorghum is grown on about 0.59 million ha and accounts for 29.4% of the total annual production (Anon., 1992*a*). Post-rainy season sorghum accounts for a major part of hybrid seed production and fetches a higher market price than the rainy season crop. This is because the low relative humidity during the post-rainy season keeps sorghum free from grain mould, a disease that severely affects grain quality during the rainy season.

During the rainy season in India (June – October), infestation of sorghum by shoot fly is negligible if sowing is done early with the first rains. Since farmers follow this simple cultural practice, less than 5% of the rainy season crop is infested. However, during the post-rainy season (October – March), sorghum is grown either on moisture stored in the soil profile or under irrigation. Post-rainy season sorghum needs to be protected against shoot fly in the early stages of plant growth because young seedlings are exposed to the second peak in fly populations that occurs in October/November (Taneja, Seshu Reddy & Leuschner, 1986). During this season, crop damage can be as high as 80% and losses in grain yield of over 50% have been reported (Nadgouda, Shastry & Kulkarni, 1974). Some sorghum is also grown from April to June to provide forage for animals during the lean summer months. The practice of growing multi-cut forage sorghum hybrids results in heavy shoot fly infestation to the extent that farmers frequently resow their crop (Dhaliwal, Mehndiratta & Brar, 1992) in the following season.

Major efforts in the management of shoot fly are devoted to breeding for plant resistance. Although several plant factors have been identified as contributing to resistance (Blum, 1963, 1968; Maiti & Bidinger, 1979; Raina, 1981; Maiti, Prasada Rao, Raju & House, 1984), breeding efforts have resulted in only marginal genetic improvement. Studies by Nwanze, Reddy & Soman (1990) and Nwanze *et al.* (1992) associated susceptibility with the presence of moisture on the unexpanded central whorl leaf of seedlings. Leaf surface wetness (LSW) was greater in susceptible cultivars than in resistant ones. The amount of LSW was associated with larval movement, its survival and deadheart formation. Further studies showed that LSW originates from the plant and is not due to condensation of moisture from the atmosphere (Sivaramakrishnan *et al.*, 1994; Sree *et al.*, 1994). Using potted seedlings, Soman *et al.* (1994) also showed that manipulating plant water potential by varying soil water status had profound effects on the production of LSW in shoot fly susceptible genotypes. In a preliminary experiment with shoot fly susceptible cultivar, CSH 5, we subjected a set of potted seedlings to moderate moisture stress and compared them with fully irrigated seedlings for LSW, shoot fly oviposition and damage (deadheart). All three parameters were drastically reduced in the moisture-stressed plants.

We then hypothesised that management of soil water in post-rainy season sorghum, can be used to manipulate LSW and therefore shoot fly incidence. This implies that, if soil moisture in irrigated sorghum could be reduced during the first four weeks after sowing (when seedlings are more prone to shoot fly attack) damage could be considerably reduced. We designed and conducted an initial set of experiments in a rainout shelter (ROS) and a subsequent field study in an Alfisol to compare water stress treatments on shoot fly incidence, crop damage and yield.

Materials and Methods

Rainout shelter

The rainout shelter (ROS) is a facility used at ICRISAT Asia Center, India, to screen crop genotypes for drought tolerance without interference from rain. This facility is equipped with a sensor that triggers the automatic movement of two transparent overhead roof shelters to cover the crop when it rains. Complete movement is accomplished in 2 min. The required quantity of water is provided to the crop only through drip irrigation. The soil type in the ROS is Alfisol and an area of 32 m × 100 m is available in experimental blocks of 16 m × 100 m. Two experiments were conducted in the ROS during the post-rainy seasons in 1989/90 and 1991/92.

Expt I: Effect of irrigation (soil moisture) on shoot fly damage and grain yield

This experiment was conducted in one block (16 m × 100 m) of the ROS with a commercial shoot fly-susceptible genotype, CSH 5. It consisted of three irrigation regimes (treatments), T1 (severe stress), 25 mm drip irrigation at sowing; T2 (moderate stress), 25 mm at sowing and 10 mm at 5 DAE and T3 (control), 25 mm at sowing and 10 mm at 5-day intervals. These regimes were maintained until 21 DAE after which all treatments were uniformly irrigated at 5-day intervals until T2 was at physiological crop maturity. The crop was sown on 15 November 1989 and each treatment consisted of one plot of 12 rows each of 25 m long at row spacing of 0.75 m. A basal application of 150 kg ha^{-1} of ammonium phosphate was applied before sowing and 100 kg ha^{-1} of urea was given at 30 days after sowing. Plants were thinned to a 10 cm spacing within rows at 10 DAE. Weeding was done manually when needed.

In order to obtain replicated observations within each treatment, five subplots each of four rows, 3 m long were randomly delineated within each plot. The following observations were recorded in each subplot: total number of plants, visual score of LSW, number of plants with eggs and total number of plants with deadheart at 21 DAE. LSW was scored visually by destructive sampling on 10 randomly selected seedlings at 10 DAE as described by Nwanze *et al.* (1990). The number of plants with eggs and therefore number of eggs/plant was obtained from a sample of 100 plants at 14 DAE. The following observations were also recorded: plant biomass at 40 DAE in each treatment from five sample areas of three rows, 2 m long; the height of 100 randomly selected plants at 60 DAE; the time to 50% flowering; time to physiological maturity and grain yield at harvest.

Expt II: Effect of soil moisture, insecticide application and genotype on shoot fly damage in sorghum

This experiment was conducted in the ROS during the 1991/92 post-rainy season. It was designed as a split-split plot with irrigation regime as the main plot, insecticide application as the subplot and genotypes (shoot fly susceptible, CSH 5 and moderately resistant, IS 1054) as the sub-subplot. The crop was sown on 18 November 1991. Irrigation treatments were the same as in Expt I. Each subtreatment consisted of a plot of six rows each of 25 m long at row spacing of 0.75 m of each genotype. In each treatment, four subplots each of three rows each of 4 m long were randomly delineated within each plot and observations recorded as in Expt I. Plant biomass was measured from three sample areas and other observations were the same as in Expt I.

In order to examine the independent effect of soil moisture conditions on crop growth and grain yield in the absence of shoot fly infestation, a similar set of treatments and subtreatments was repeated in the second block of the ROS where shoot fly infestation was controlled by the application of cypermethrin at 45 g a.i. ha^{-1} at weekly intervals from 7–28 DAE.

Expt III: Effect of soil moisture and insecticide application on shoot fly damage in sorghum

This experiment was conducted on a 1 ha field of an Alfisol during the 1991/92 post-rainy season. The shoot fly susceptible genotype CSH 5 and five irrigation treatments were used. There was no rain between 22 October 1991 (18 mm) and 29 April 1992. All treatments received 25 mm sprinkler irrigation at sowing on 12 November 1991. Thereafter, the following irrigation regimes were applied: T1 (severe stress), no irrigation until 21 DAE; T2 (slightly moderate stress), 10 mm by sprinkler irrigation at 5 DAE; T3 (moderate stress), 20 mm at 10 DAE; T4 (partially irrigated treatment), 30 mm at 15 DAE and T5 (control), normal furrow irrigation applied every 10 days. At 21 DAE, all treatments received normal furrow irrigation until crop physiological maturity.

Plots were arranged in a split plot design with irrigation treatment as the main plot and insecticide application as the subplot. Each subplot consisted of 20 rows each of 25 m long at row spacing of 0.75 m. In each treatment, five subplots each of six rows each of 6 m long were randomly delineated within each plot and observations recorded as in Expt I. Biomass data were obtained from four sample areas of four rows each of 2 m long. Insecticide was applied as in Expt II and all agronomic practices were the same as in Expt I.

Soil moisture content

Soil moisture content was measured in each treatment of Expts II and III, 24 h before sowing and one day after each irrigation until 21 DAE. For each treatment, three soil samples in Expt II and five in Expt III, were taken at random with a metal soil core at 10, 20 and 30 cm depths for the determination of gravimetric soil moisture content.

Statistical analysis

Data were subjected to analysis of variance (ANOVA) using general linear models (Anon., 1985). Significant differences in means between treatments were separated using the least significant difference (LSD) (Snedecor & Cochran, 1967).

Table 1. *Effect of irrigation regimes on shoot fly damage and yield under rainout shelter conditions*

Treatment		LSW (score)	Plants with eggs (%)	Plants with dead-heart (%)	Biomass at 40 DAE (t ha^{-1})	Grain yield (t ha^{-1}) Main stem	Tillers	Total
T1		1.6 ± 0.1c	7.1 ± 3.2c	19.5 ± 5.2c	0.4 ± 0.1b	2.6 ± 0.3a	1.0 ± 0.2b	3.6 ± 0.3a
T2		3.3 ± 0.2b	33.2 ± 1.9b	61.9 ± 3.3b	0.7 ± 0.0a	3.1 ± 0.2a	1.3 ± 0.1b	4.4 ± 0.2a
T3		4.5 ± 0.1a	58.5 ± 5.4a	87.8 ± 5.5a	0.5 ± 0.1a	1.0 ± 0.4b	2.7 ± 0.3a	3.7 ± 0.1a
Mean square								
Source	df							
Irrigation	2	10.6‡	3299.1‡	5944.6‡	0.1	4.7*	3.2†	0.8
Error	8	0.1	505.7	127.7	0.0	0.5	0.2	0.2
r^2		1.0	0.9	0.9	0.5	0.8	0.8	0.6
CV (%)		7.7	24.1	20.0	32.2	31.2	26.8	12.6

Means within a column followed by the same letter are not significantly different at $P = 0.05$; Least Significant Difference.

Visual score on a 1–5 scale, where 1 = no apparent moisture and 5 = dense droplets.

T1–T3 = irrigation treatments, where T1 = severe stress and T3 = no moisture stress (control).

*$P < 0.05$, †$P < 0.01$, ‡$P < 0.001$

Results

Expt I: Effect of irrigation (soil moisture) on shoot fly damage and grain yield

Subjecting plants to extreme soil moisture conditions during the early part of seedling growth reflected changes in LSW production, insect infestation, crop damage and plant growth and development. LSW scored on a 1–5 scale (visual rating, where 1 = no apparent moisture and 5 = dense droplets) decreased from 4.5 in the control (T3) to 3.3 in the moderate stress (T2), and 1.6 in severe stress (T1) (Table 1). Shoot fly infestation (oviposition) and crop damage (deadheart) were lowest in T1 and highest in T3. Plant biomass was highest in T2 and flowering occurred earlier by 7 and 14 days in this treatment than in T3 and T1 respectively. Due to tillering in T3, following heavy shoot fly damage, crop maturity was delayed by 10 days. The grain yield in T2 plots, which received only 10 mm irrigation at 5 DAE for the first 21 days was 4.4 t ha^{-1} compared with 3.7 t ha^{-1} in the control (T3), which received "normal" full irrigation during the same period. The percentage grain yield gain in T2 over T3 was almost 20%.

Expt II: Effect of irrigation, insecticide application, and genotype on shoot fly damage and grain yield

Irrigation had no effect on LSW in moderately resistant IS 1054 in any treatment (Table 2). On the other hand, CSH 5 responded to changes in irrigation regime with fully irrigated treatments (Unprotected/T3/CSH 5 and Protected/T3/CSH 5) having higher LSW values than other treatments.

With the exception of Protected/T1/CSH 5 greater than Protected/T1/IS 1054 for percentage plants with eggs and the latter greater than the former for plants with deadheart, oviposition and deadheart followed the same pattern, with CSH 5 showing higher shoot fly oviposition and crop damage than IS 1054. The above observation had more pronounced differences in unprotected than in protected plots and was highest in unprotected, fully irrigated CSH 5 plots (Unprotected/T3/CSH 5) (Table 2). The interactions between insecticide × irrigation, insecticide × genotype and irrigation × genotype were significant.

There were statistical differences in plant biomass, main stem and tiller yields which were higher in all cases for T3. Plant biomass had a positive relationship with main stem yield for both CSH 5 and IS 1054. It was highest in the Protected/T2 treatments in both genotypes. However, a more striking result was that for both genotypes, withholding irrigation after crop emergence in Unprotected/T1 resulted in higher plant biomass and total grain yield compared with Protected/T3. Additionally, without insecticide protection, minimum irrigation (Unprotected/T1) reduced shoot fly damage to the same level as that with maximum irrigation plus insecticide protection (Protected/T3).

For CSH 5, the percentage total yield gains due to withholding irrigation in Unprotected/T1 and Unprotected/T2 over Unprotected/T3 (control) were 10% and 30%. In IS 1054, these gains were 20% and 70% respectively. The total grain yield loss for CSH 5 in T1, T2 and T3 were 8.2%, 12.9% and 39.0% and for IS 1054 they were 30.9%, 21.6% and 26.5% respectively. In CSH 5, the yield loss due to shoot fly alone was 20.1% and to excess moisture alone was 54.3%, so the total loss was 74.4%. In IS 1054, the yield loss due to shoot fly alone was 26.5% and to excess moisture alone was 58.4%, so the total loss was 84.4%. The total yield gains from spraying CSH 5 in T1, T2, and T3 were 7.7%, 14.9% and 64.0%, and from spraying IS 1054 were 44.6%, 27.6% and 36.0%.

Fig. 1 presents the soil water content measured at three depths at five crop growth stages. As expected the soil water content in T3 was always highest. At 9 DAS, there was no significant difference in the water content at 0–15 cm for T1 and T2, the moderately stressed

Table 2. *Effect of irrigation regimes, insecticide application and genotype on shoot fly damage and yield in the rainout shelter*

Treatment	df	LSW (score)	Plants with eggs (%)	Plants with dead-heart (%)	Biomass at 40 DAE (t ha^{-1})	Grain yield (t ha^{-1}) Main stem	Tillers	Total
Pr+/T1/Gen 1		1.9 ± 0.2c	5.6 ± 1.6de	0.3 ± 0.3c	1.3 ± 0.1a	3.0 ± 0.2abc	0.4 ± 0.0ef	3.3 ± 0.3abcd
Pr+/T2/Gen 1		2.2 ± 0.1bc	27.2 ± 7.6bc	6.1 ± 2.9c	1.5 ± 0.0a	3.4 ± 0.2a	0.5 ± 0.1cde	3.9 ± 0.3a
Pr+/T3/Gen 1		2.9 ± 0.2a	18.1 ± 6.1cd	3.3 ± 1.2cd	0.4 ± 0.1de	2.3 ± 0.5cd	0.4 ± 0.0ef	2.6 ± 0.4de
Pr−/T1/Gen 1		1.9 ± 0.2c	23.5 ± 5.4bc	5.3 ± 0.8c	0.9 ± 0.1bc	3.3 ± 0.2ab	0.4 ± 0.1ef	3.6 ± 0.3ab
Pr−/T2/Gen 1		2.3 ± 0.2b	34.3 ± 4.4b	22.9 ± 5.2b	1.0 ± 0.1b	2.8 ± 0.2abc	0.7 ± 0.1bc	3.4 ± 0.2abcd
Pr−/T3/Gen 1		2.7 ± 0.1a	66.6 ± 7.3a	58.0 ± 5.3a	0.1 ± 0.0f	0.2 ± 0.1g	1.4 ± 0.1a	1.6 ± 0.1fg
Pr+/T1/Gen 2		1.0 ± 0.0d	4.4 ± 2.7e	6.4 ± 3.0c	0.9 ± 0.1bc	2.5 ± 0.4bcd	0.7 ± 0.1bcd	3.1 ± 0.3bcd
Pr+/T2/Gen 2		1.1 ± 0.1d	4.2 ± 1.5e	4.1 ± 0.8c	1.0 ± 0.1b	2.6 ± 0.2abc	0.9 ± 0.1b	3.5 ± 0.2abc
Pr+/T3/Gen 2		1.3 ± 0.2d	6.7 ± 1.5de	0.8 ± 0.8c	0.2 ± 0.0ef	1.2 ± 0.2ef	0.1 ± 0.0g	1.4 ± 0.2fg
Pr−/T1/Gen 2		1.1 ± 0.1d	1.7 ± 1.1e	0.8 ± 0.8c	0.3 ± 0.1ef	1.8 ± 0.2de	0.4 ± 0.0ef	2.2 ± 0.2ef
Pr−/T2/Gen 2		1.0 ± 0.0d	3.6 ± 1.5e	4.9 ± 2.1c	0.7 ± 0.2cd	2.3 ± 0.4cd	0.5 ± 0.1de	2.7 ± 0.4cde
Pr−/T3/Gen 2		1.0 ± 0.0d	17.6 ± 5.2cd	22.1 ± 3.3b	0.2 ± 0.1ef	0.8 ± 0.2fg	0.2 ± 0.0fg	1.0 ± 0.2g
Mean square								
Source	df							
Spray	1	0.1	2194.0‡	2882.1‡	1.2‡	5.3†	0.1*	3.7†
Irrigation	2	0.9‡	1367.0‡	1313.5‡	2.4‡	13.3‡	0.2†	13.6‡
Genotype	1	13.6‡	6263.6‡	1069.9‡	1.0‡	4.7†	0.4†	7.7‡
Spray × irrigation	2	0.1	806.8	1595.7‡	0.1	1.3*	0.7‡	0.1
Spray × genotype	1	0.0	1453.5†	1205.6‡	0.0	0.3	1.1‡	0.2
Irrigation × genotype	2	0.5	398.0*	399.6‡	0.2*	0.6	0.9‡	0.1
Spray × irrigation × Gen.	2	0.0	225.8	140.4*	0.0	1.6*	0.1†	0.9
Error	33	0.1	80.4	29.2	0.0	0.3	0.0	0.3
r^2		0.9	0.9	0.9	0.9	0.8	0.9	0.8
CV (%)		13.3	50.4	48.1	24.5	26.5	26.4	20.9

PR− unprotected, PR+ protected with insecticide, T1–T3 = irrigation treatments, where T1 = severe stress and T3 = no moisture stress (control), Gen 1 = CSH 5 (susceptible), Gen 2 = IS 1054 (moderately resistant).

Means within a column followed by the same letter are not significantly different at $P = 0.05$; Least Significant Difference.

$^*P < 0.05$, $^\dagger P < 0.01$, $^\ddagger P < 0.001$.

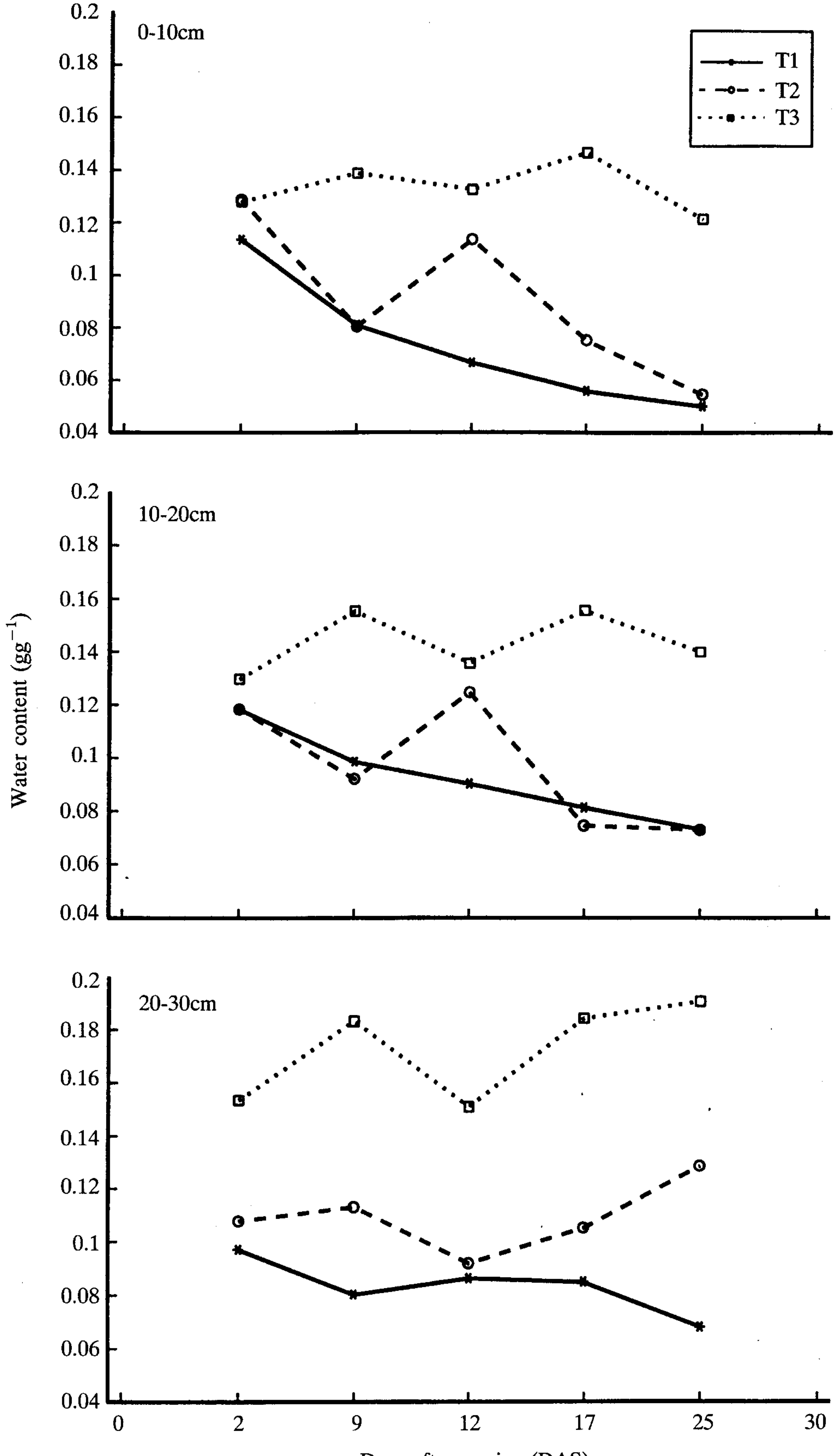

Fig. 1. Soil water content in various irrigation treatments from the days after sowing (DAS) measured at different depths in rainout shelter. T1–T3 = irrigation treatments, where T1 = severe stress, T2 = moderate stress, and T3 = no moisture stress (control).

Table 3. *Effect of irrigation regimes and insecticide application on shoot fly damage and yield under field conditions*

Treatment	df	LSW (score)	Plants with eggs (%)	Plants with dead-heart (%)	Biomass at 40 DAE ($t\ ha^{-1}$)	Grain yield ($t\ ha^{-1}$) Main stem	Tillers	Total
Pr+T1		2.5 ± 0.2d	3.2 ± 1.2e	1.3 ± 0.6f	1.2 ± 0.1a	2.9 ± 0.1a	0.3 ± 0.0f	3.1 ± 0.1ab
Pr+/T2		2.7 ± 0.4bcd	3.8 ± 2.3e	0.8 ± 0.2f	1.1 ± 0.1a	2.4 ± 0.3bc	0.3 ± 0.0ef	2.7 ± 0.3bc
Pr+/T3		2.7 ± 0.1bcd	16.2 ± 2.1cd	8.2 ± 1.5e	1.2 ± 0.2a	2.5 ± 0.1ab	0.5 ± 0.0d	3.0 ± 0.1ab
Pr+/T4		2.7 ± 0.2bcd	10.0 ± 1.6de	1.2 ± 0.3f	1.0 ± 0.0ab	2.8 ± 0.2ab	0.4 ± 0.1def	3.2 ± 0.2a
Pr+/T5		3.0 ± 0.1abc	19.0 ± 3.0cd	8.2 ± 1.5e	0.9 ± 0.1bc	2.1 ± 0.1cd	0.4 ± 0.1def	2.5 ± 0.1cd
Pr−/T1		2.6 ± 0.2cd	18.4 ± 1.8cd	9.8 ± 0.9e	0.7 ± 0.1cd	2.0 ± 0.1d	0.3 ± 0.0f	2.2 ± 0.2d
Pr−/T2		2.8 ± 0.2bcd	22.4 ± 3.9c	19.7 ± 4.5de	0.7 ± 0.1cd	1.7 ± 0.2d	0.5 ± 0.1de	2.2 ± 0.2d
Pr−/T3		3.0 ± 0.1abc	74.6 ± 5.1b	64.0 ± 4.2c	0.7 ± 0.1cd	0.8 ± 0.2e	1.3 ± 0.1b	2.1 ± 0.1d
Pr−/T4		3.1 ± 0.2ab	70.0 ± 3.5b	72.0 ± 3.0b	0.6 ± 0.1de	0.5 ± 0.1ef	1.6 ± 0.1a	2.1 ± 0.1d
Pr−/T5		3.3 ± 0.1a	92.8 ± 4.5a	84.3 ± 2.4a	0.4 ± 0.0e	0.2 ± 0.1f	1.0 ± 0.1c	1.2 ± 0.1e
Mean square								
Source	df							
Spray	1	0.4*	25538.0‡	26512.6‡	2.3‡	27.1‡	3.6‡	11.0‡
Irrigation	4	0.3*	4040.0‡	3212.8‡	0.2†	2.2‡	1.0‡	1.2‡
Spray × irrigation	4	0.0	1761.8‡	2348.4‡	0.0	1.1‡	0.6‡	0.2
Error	36	0.1	51.8	22.5	0.0	0.1	0.0	0.1
r^2		0.6	1.0	1.0	0.8	0.9	0.9	0.8
CV(%)		10.1	21.8	17.6	18.3	18.9	22.7	13.3

PR− unprotected, PR+ protected with insecticide, T1–T5 = irrigation treatments, where T1 = severe stress and T5 = no moisture stress (control).
Means within a column followed by the same letter are not significantly different at $P = 0.05$; Least Significant Difference.
$*P < 0.05$, †$P < 0.01$, ‡$P < 0.001$.

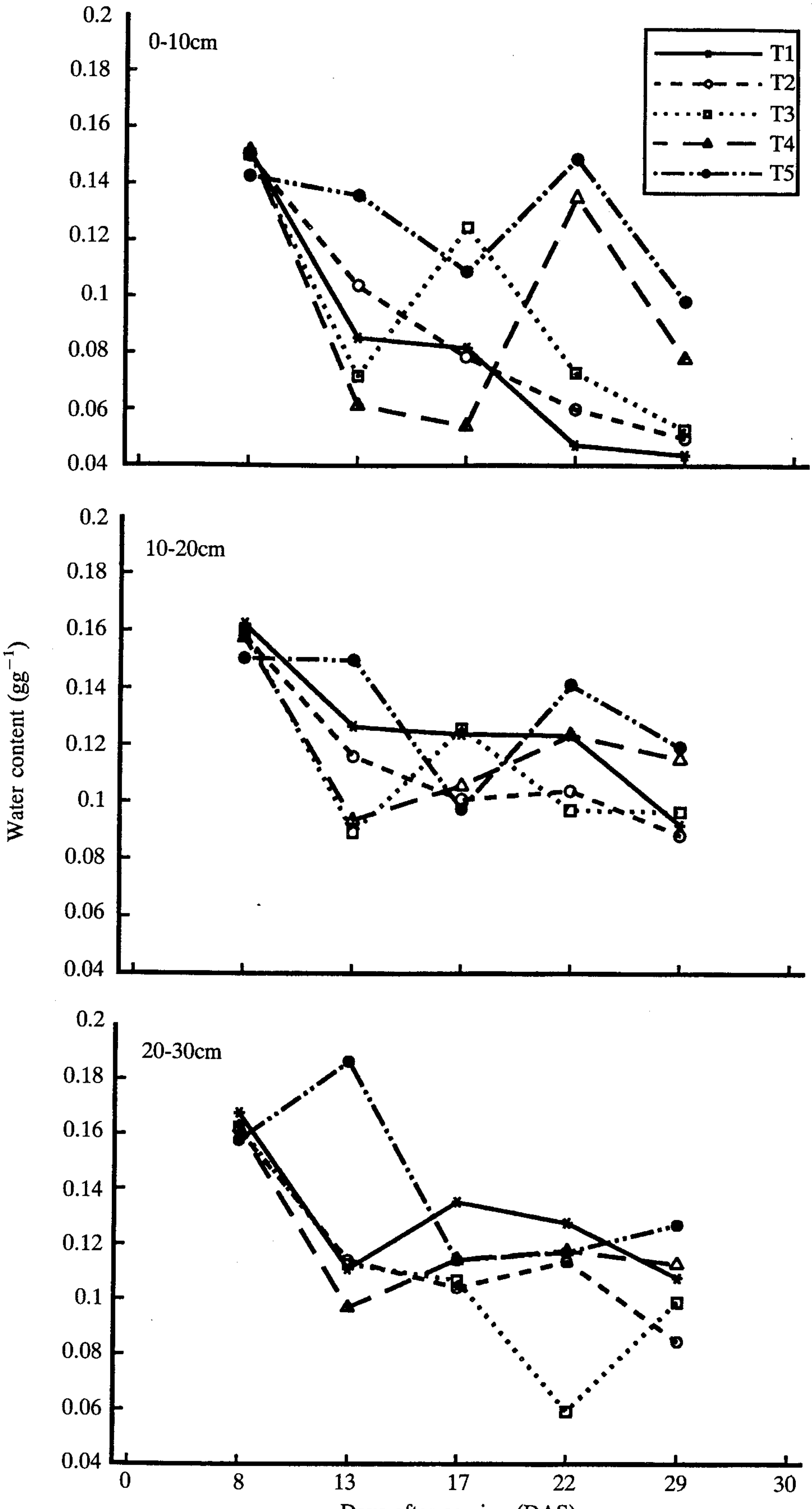

Fig. 2. Soil water content in various irrigation treatments from the days after sowing (DAS) measured at different depths in the field. T1–T5 = irrigation treatments, where T1 = severe stress, T2 = slightly moderate stress, T3 = moderate stress, T4 = partially irrigated treatment, and T5 = no moisture stress (control).

treatment T2 had more water than T1 at a depth of 15–30 cm. At 12 DAS after 10 mm water had been applied at 5 DAE to T2, there were clear differences between the moisture treatments with T3 > T2 > T1. At 17 DAS, there was no difference in moisture content between T1 and T2. At 25 DAS, T1 and T2 had similar water contents at a depth of 0 – 15 cm, but there was more water content in T2 than in T1 at 15 – 30 cm.

Experiment III: Effect of soil moisture and insecticide application on shoot fly damage in sorghum

The field studies showed that CSH 5 responded to irrigation treatments thus exhibiting significant differences ($P < 0.05$) in LSW (Table 3). There were highly significant differences ($P < 0.001$) between treatments and for insecticide by irrigation interactions for shoot fly oviposition and deadhearts. The percentage of plants with eggs and deadhearts was greater in the full irrigation treatment (T5) than in the severe moisture stress treatment (T1) irrespective of whether the plots were sprayed or not.

There were significant differences ($P < 0.001$) in biomass and main stem yield for the insecticide protected and unprotected treatments. It was also noted that under severe stress and no insecticide application (Unprotected/T1), infestation, damage and grain yield were not significantly different from the fully irrigated and protected (Protected/T5) treatment. However, with protection, the highest moisture stressed treatment (Protected/T1), produced higher biomass and main stem grain yield than plots which received full irrigation (Protected/T5) during the same period (Table 3).

Without insecticide protection, the total grain yields in all irrigation treatment were significantly more than the control (T5), and the percentage increases were 88.1 (T1), 83.1 (T2), 74.6 (T3) and 81.4 (T4). The total grain yield loss for CSH 5 in T1, T2, T3, T4 and T5 were 28.4%, 20.0%, 31.6%, 32.5% and 52.2% respectively. The yield loss due to shoot fly alone was 32.9% and to excess moisture alone was 45.0%, so the total loss was 77.9%. The total yield gains from spraying CSH 5 in T1, T2, T3, T4 and T5 were 39.6%, 25.0%, 46.1%, 48.1% and 109.3%. The differences in tillers and total crop yield were highly significant ($P < 0.001$) between insecticide protected plots, irrigation treatments and their interactions (Table 3).

Water content measured at three depths during five crop growth stages are presented in Fig. 2. At 8 DAS the water content was not different between the treatments at the three depths. At 13 DAS, there were significant differences in water content of the treatments in 0 – 10 cm depth. Except T2 and T4, there were significant differences between treatments in 10 – 20 cm depth. Except at 8 and 17 DAS, the control treatment T5 had more water at the three depths compared to the other treatments. At 17 DAS, the water content of T3 > T5 > T1 = T2 > T4. This situation reversed at 29 DAS when water content at T5 was greater than that at T4 at the three depths. There was not much difference in 0 – 15 cm depth between the water content of T1, T2 and T3 at 29 DAS. Beyond 15 cm, water content in T1 was greater than that in T3 and T2 in that order.

Discussion

There was a fluctuating trend in soil water content as a function of time. These trends affected production of leaf surface wetness (LSW) on the central whorl leaf of seedlings of sorghum genotypes. In Expt I, although moisture stress (T1) resulted in reduced LSW, egg laying and crop damage, this did not translate into better crop growth, grain and fodder yield (Table 1). However, there was a significant pay-off from moderate moisture stress (T2) in the

ROS experiment with gains in plant biomass and total grain yield of 23.53% and 16.36% of T2 over T3. This indicates a threshold of soil moisture at which irrigation management has an overall positive effect on shoot fly infestation and crop growth. Excessive soil moisture in the early stages of plant growth affects soil aeration and interferes with the establishment of the secondary root system resulting in poor crop establishment in the early stages of crop growth. Additionally, low post-rainy season temperatures in November (max = 29.3°C, min = 15.6°C) would slow down plant growth thereby extending the susceptible period to shoot fly damage. In Expt 2, LSW was higher in plots of susceptible CSH 5 than in moderately resistant IS 1054. However, LSW in moderately resistant IS 1054 was similar in all irrigation treatments, in contrast to CSH 5 (Table 2). This agrees with earlier studies that indicated that the mechanism by which water is transferred to the leaf surface in susceptible genotypes (CSH 5) appears to be lacking in resistant ones (IS 1054) (Soman *et al.*, 1994). But full irrigation did affect plant growth and biomass production as well as overall grain yield in IS 1054 whether protected or not (Protected/T3/IS 1054 and Unprotected/T3/IS 1054) compared to moisture stressed treatments of this genotype (Table 2). In both genotypes, moisture stress alone gave higher biomass and grain yield in T1 and T2 than in insecticide protection with full irrigation, confirming the result obtained in Expt I.

Data from the unprotected treatments in Expt III clearly showed the benefits from reduced irrigation during early crop growth stages. The differences in LSW between T1-T5 in the field (Expt III, Table 3) were not as pronounced as in the ROS (Expt II, Table 2) due to higher initial soil moisture content in the field (Fig. 2). As shown in Fig. 1, at the initial stages of the study, we were able to obtain in the ROS drier soil conditions that were not possible in the field experiment. However, the differences in soil moisture between 8–13 DAS in Expt III were significant enough to affect shoot fly oviposition and seedling damage. The most significant result in this study is that reducing irrigation in the first 4 wk after seedling emergence results in the same or higher grain yield than insecticide protection with full irrigation.

Soil water management as a cultural control tactic has been shown to control the rice weevil, *Lissorhoptrus oryzophilus* Kuschel in Louisiana, USA (Quisenberry *et al.*, 1992). Their study involved the removal of water to alter the habitat necessary for larval survival. Similarly, in Colombia, water drainage in rice fields (weekly flush as against permanent flooding) resulted in fewer eggs, mines and pupae of the rice leafminer *Hydrellia wirthi* Korytkowsky (Pantoja *et al.*, 1993). Evidence from studies in southern USA on the influence of irrigation on soybean genotypes to soybean looper (Lambert & Heatherly, 1991, 1995) revealed that defoliation by insects of irrigated plants of both genotypes was more than 50% greater than defoliation of non-irrigated plants. Although Kimberling, Scott & Price (1990) attributed susceptibility to attack by the leaf-galling phylloxerid *Viteus vitifoliae* to plant (wild grape) vigour without stress, White (1974), however, suggested plant stress as the cause of outbreaks of looper caterpillars, *Selidosema suavis* in a plantation of *Pinus radiata* in New Zealand. In our studies, irrigation water was provided until physiological maturity. This facilitated recovery from shoot fly damage and higher tiller grain yield in fully irrigated treatments thus partially masking the initial effect on poorer crop growth and higher shoot fly damage. Under normal conditions, this would not occur in farms where sorghum is grown on moisture stored in the soil profile (i.e. post-rainy season cropping).

An obstacle to the immediate application of our results by farmers is that our experiments were conducted in Alfisols which constitute a small fraction of post-rainy season sorghum ecosystems. Vertisols are normally used to grow post-rainy season sorghum. Our choice of an Alfisol was due to the location of the ROS on an Alfisol and the need to conduct the experiments with minimum interference from rainfall. Traditionally, post-rainy season sorghum is sown in early to mid October in India and this period coincides with a window of lower shoot fly infestation (Anon., 1992*b*). However, damage to crops sown in this period is relatively high. Transferring our results into Vertisol conditions would be a major contribution to shoot fly management. Efforts will be made to duplicate our results in a Vertisol.

The immediate implication of our finding is the actual savings in production inputs (i.e. cost of chemical insecticides and irrigation water), which resource poor farmers can ill afford. Added to the savings in chemical inputs, soil management in post-rainy season production has tremendous potential benefits not only relevant to India where shoot fly is an endemic constraint on post-rainy season sorghum production, but also in non-endemic countries like Sudan with over 4.5 million ha of irrigated sorghum.

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