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**L. Mateos · E. C. Mantovani · F. J. Villalobos**

# Cotton response to non-uniformity of conventional sprinkler irrigation

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**Abstract** Sprinkler irrigation systems are characterized by some degree of non-uniformity. The effect of non-uniformity on crop yield has been modelled in different ways but experimental studies are scarce. An experiment was conducted comparing the effects of two levels of uniformity (mean Wilkox and Swailes' uniformity coefficients of 80% and 52%) at two levels of water supply (about 400 and 260 mm for the whole irrigation season) on cotton production. Final yield was not affected either by uniformity or by the amount of water supplied. Vegetative growth was higher in the full irrigation treatments. Maximum leaf area index did not differ statistically between uniformity treatments. The lack of differences was attributed to the curvilinear shape of the yield function and to the dampening of the variations in applied water in the soil, as the coefficient of variation in applied water was more than twice the coefficient of variation of infiltrated water. These results suggest that non-uniformity of conventional sprinkler irrigation has a lower impact on cotton crop performance than expected from previous simulation studies.

## Introduction

A severe drought affected southern Spain during the 5-year period 1991–1995. As a consequence, the Water Commission of the Guadalquivir Basin had to suspend the delivery of water for irrigation. Cotton acreage in the basin has decreased from 62,000 ha in 1991 to 24,000 ha in 1994. There is also a shift from furrow irrigation, the traditional method for cotton crops, to more efficient methods, such as sprinkler and drip irrigation, associated with the need to save water.

Sprinkler irrigation systems are characterized by some degree of non-uniformity in the application of water. Water application uniformity potentially influences crop yield and irrigation efficiency. Warrick and Gardner (1983) analysed theoretically the effect on yield of soil spatial variability and irrigation non-uniformity. They showed that increasing irrigation non-uniformity decreases average yield. Letey et al. (1984) did a similar analysis extended to crops with curvilinear yield functions.

The uniformity of sprinkler irrigation is usually quantified by the coefficient of uniformity proposed by Christiansen (1942). Wilkox and Swailes (1947) proposed a similar coefficient of uniformity based on the statistical standard deviation and mean of water depth distribution:

$$WSUC = (1 - CV)100 \qquad (1)$$

where CV is the coefficient of variability (standard deviation/mean). Such coefficients seem to be insufficient to quantify the influence of non-uniformity on crop yield and drainage losses, since they do not take into account some effects related to the crop morphology, soil characteristics and spatial pattern of variation of the applied water. The uniformity coefficients are often determined from measurements with water collection cans located above the crop or on bare soil. However, Ayars et al. (1991a) found that a cotton crop tends to improve the uniformity when water flows through the canopy. Wallach (1990) demonstrated theoretically that lateral movement of soil water smooths the spatial variation of water flux as the wetting front advances. Stern and Bresler (1983) showed that redistribution of soil water after irrigation caused corn yield to be more uniform than applied water.

Modelling the effect of irrigation non-uniformity on yield has been widespread and productive. However, field data for validating models are very scarce. The most extensive work is that developed in California for sugar beet (Ayars et al. 1990; Ben-Asher and Ayars 1990) and cotton

L. Mateos (✉)
Instituto de Agricultura Sostenible, CSIC,
Apdo 4084, E-14080 Cordoba, Spain

E. C. Mantovani[1] · F. J. Villalobos
Departamento de Agronomia, Universidad de Cordoba,
Apdo 3048, E-14080 Cordoba, Spain

*Present address:*
[1] Departamento de Engenharia Agricola, Universidade Federal de Viçosa, 36570 Viçosa-MG-Brasil, Brasil

(Ayars et al. 1991b), using a linear-move irrigation machine that can produce different uniformities and scales of variation. These studies have shown important effect of the non-uniformity pattern of water application on crop yield and drainage losses. It is therefore necessary to generate field data for non-uniformity from sprinkler configurations different to those produced by a linear-move machine. One such configuration should be that of conventional sprinkler irrigation, the most common in use in southern Spain and other irrigation areas of the world. In contrast with the variation in the amount of water applied by a linear-move irrigation system, the configuration of conventional sprinkler irrigation normally produces two-dimensional patterns with large scales of variation.

The objective of this study was to assess the spatial variability in soil water and cotton yield in response to uniformity and depth of water applied by a conventional sprinkler irrigation system.

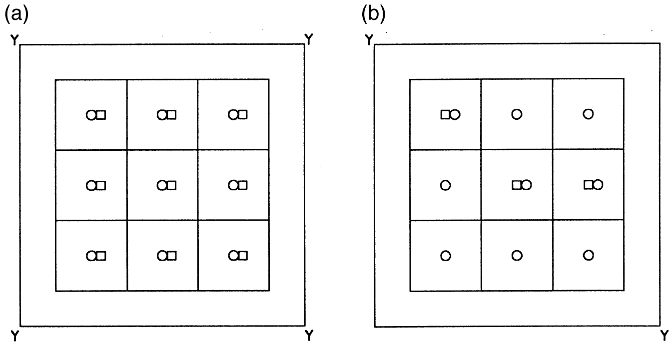


**Fig. 1** Experimental layout of sprinklers, catch cans and neutron probe access tubes in the low-uniformity treatments (L1-C2 and L2-C2) (**a**) and the high-uniformity treatments (L1-C1 and L2-C1) (**b**). Y Sprinkler, ○ Catch can, □ Neutron probe access tube

## Materials and methods

### Experimental field

The experimental field was a 100×70 m plot located at the Agriculture Research Centre in Cordoba, Spain. The plot was sown on 7 May 1993 with an American cultivar (Coker-310) of cotton along 0.75-m spaced rows giving a planting density of 100,000 plants/ha after thinning. The cotton cultivar Coker-310 is the most extensively grown in Spain. Its water production function is curvilinear when grown in Cordoba (Orgaz et al. 1992). Cotton management (fertilization and pest control) followed the standard practice in the area. The soil was a typic xerofluvent with loam texture and a depth that exceeded 3 m (Table 1).

Four treatments resulting from the combination of optimum and suboptimum amounts of applied water (L1 and L2, respectively) with high and low uniformity (C1 and C2, respectively) were compared. Each treatment was replicated three times in a randomized complete-block design. The plots were 12×12 m in size. The sprinklers used (VYR-50) were sectorial with a nozzle 4 mm in diameter. Pressure in the sprinklers was kept between 2.5 and 3 kg/cm$^2$. The C1 treatment was obtained by locating one sprinkler on each corner of the plots and irrigating with a rotation angle of 180° in order to obtain a rain intensity no greater than 15 mm/h. The C2 treatment was obtained by locating two sprinklers diagonally opposite each other on the plots (Fig. 1) and disrupting the jet of one of them. The rotation angle (somewhat above 110°) was adjusted to give the same water supply rate as in C1. The plots were located in the field at distances between 6 and 12 m, to avoid interference between adjacent plots.

**Table 1** Soil bulk density and texture at the experimental site

| Depth (m) | Bulk density (Mg/m$^3$) | Texture (%) | | |
|---|---|---|---|---|
| | | Clay | Sand | Silt |
| 0–0.15 | 1.2 | 14 | 39 | 47 |
| 0.15–0.30 | 1.4 | 13 | 39 | 48 |
| 0.30–0.50 | 1.5 | 14 | 39 | 47 |
| 0.50–0.70 | 1.4 | 12 | 47 | 41 |
| 0.70–0.90 | 1.4 | 14 | 48 | 38 |

### Irrigation

A preplant uniform sprinkler irrigation of 60 mm was applied on 13 April. A first irrigation of 30 mm was applied on 30 June before imposing the irrigation treatments. Rainfall during the crop growing season was 60 mm from planting to the first irrigation date and 160 mm from the last irrigation to 31 October. There was no rainfall during the irrigation season. Irrigation intervals varied from 5 to 14 days (Table 2). Irrigation amounts were calculated in order to refill the profile in L1–C1. The amount of water applied to L2 was 60% of that applied to L1 in order to provoke severe water stress. The C1 treatments were irrigated early in the morning to avoid wind effects on the application uniformity. The C2 treatments were irrigated just after C1.

### Water measurements

Each plot was divided into a grid of nine 3×3 m subplots (Fig. 1). Catch cans 110 mm in diameter were located just above the crop in the centre of each subplot. Water was collected in plastic bottles connected to the cans by a tube to prevent evaporation. The amount of water collected was measured the day after irrigation. Neutron probe access tubes were installed in the centre of each subplot in the C2 treatments and in the centre of three of the nine subplots in the C1 plots (Fig. 1b). Soil water content was measured with a neutron probe calibrated in the field separately for the upper 15 cm and for the layers below. Neutron probe readings were taken at 0.15-m intervals down to 0.3 m and at 0.3-m intervals from 0.3 m to 2.7 m. Soil water content measurements were made the day before, and 2 days after each irrigation. The amount of infiltrated water was estimated as the difference between the post-irrigation and pre-irrigation neutron probe measurements plus the crop evapotranspiration (ET) during the period between both measurements. This ET was estimated using Ritchie's (1972) model. Maximum crop evaporation in Ritchie's model was obtained by multiplying a crop coefficient of 1.15 (Mateos et al. 1991b) by the reference grass ET measured in a weighing lysimeter located 700 m from the experimental field. Deep percolation was negligible since the lower part of the soil profile (below 2.0 m) was initially rather dry and the applied water was never enough to increase its water content.

ET was estimated by the sum of differences between neutron probe measurements after an irrigation and before the next irrigation, adding the ET estimation for the periods between readings before and after each irrigation obtained as described above. Outside the irrigation season, ET was obtained by water balance taking into account measured rainfall. Transpiration (T) was calculated as ET minus soil evaporation estimated with Ritchie's model.

**Table 2** Applied irrigation depth (*AW*, mm), Wilcox and Swailes uniformity coefficient (*WSUC*, %) and date of each of the seven irrigations. *L1* and *L2*, mean optimum and suboptimum applied water depth, respectively; *C1* and *C2*, mean high and low uniformity, respectively

| Treatment | Irrigation number and date | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 (17 Jul) | | 2 (22 Jul) | | 3 (28 Jul) | | 4 (4 Aug) | | 5 (14 Aug) | | 6 (24 Aug) | | 7 (7 Sep) | |
| | AW | WSUC | AW | WSUC | AW | WSUC | AW | WSUC | AW | WSUC | AW | WSUC | AW | WSUC |
| L1-C1 | 45 | 86 | 81 | 85 | 49 | 88 | 61 | 82 | 47 | 78 | 76 | 79 | 48 | 83 |
| L1-C2 | 43 | 70 | 76 | 55 | 38 | 55 | 65 | 56 | 82 | 53 | 50 | 52 | 43 | 29 |
| L2-C1 | 24 | 80 | 45 | 68 | 30 | 70 | 33 | 83 | 35 | 79 | 67 | 78 | 34 | 77 |
| L2-C2 | 28 | 75 | 42 | 40 | 23 | 57 | 33 | 58 | 50 | 64 | 49 | 40 | 28 | 25 |

### Crop measurements

Crop growth and its variability were determined by measuring periodically (a total of five measurements) the leaf area index (LAI) of each subplot with a Plant Canopy Analyzer (model LI-COR 2000, Li-Cor, Lincoln, Nebr., USA). Yield was determined for each subplot at three harvesting times by hand picking the cotton seed of a centred 2.5-m segment of the three central rows of each subplot. Cotton seed was oven dried at 60 °C for 48 h.

### Determination of variability

Spatial variability in irrigation, change in soil water content, LAI and yield were obtained from the field measurements taking into account the measurement error. It was assumed that there were no systematic errors in the measurement of any of the variables. Therefore, the measured variance ($\sigma_v{}^2$) of a variable $v$ (applied water, change in soil water content, LAI or yield) can be expressed as the sum:

$$\sigma_v{}^2 = \sigma^2_{sv} + \varepsilon^2_v \tag{2}$$

where $\sigma^2_{sv}$ is the variance of variable $v$ due to spatial variability and $\varepsilon^2_v$ is the square of the measurement error of that variable.

The LAI measured with the fish-eye sensor corresponds roughly to the area of yield determination. However, it exhibits an error due to small variations in the location of the sensor below the canopy. This error ($\varepsilon_{\mathrm{LAI}}$) was estimated under a homogeneous cotton canopy giving values between 0.18 and 0.29 when the LAI varied from 1 to 4.6. The average value (0.23) was taken for this analysis.

It was assumed that the water collected in subplot-centered catch cans represented the average for the subplot. The error in this measurement was estimated from sets of catch cans distributed within a small area and irrigating with the VYR-50 sprinkler. The coefficient of variation ($\mathrm{CV_{cc}}$) obtained was 0.013. For $N$ irrigations, each of $x_i$ mm, the measurement error of applied water is:

$$\varepsilon^2_{\mathrm{cc}} = \mathrm{CV}^2_{\mathrm{cc}} \sum_{i=1}^{N} x_i^2 \tag{3}$$

The measurement error in the determination of the change in soil water content ($\varepsilon_{\Delta \mathrm{SW}}$) was attributed to the instrument error, assuming that the neutron probe integrates the soil water content of the subplot and there is no bias in the calibration of the neutron probe. Therefore:

$$\varepsilon^2_{\Delta \mathrm{SW}} = 2 N e^2_{\mathrm{np}} \sum_{i=1}^{M} d_j^2 \tag{4}$$

where $e^2_{\mathrm{np}}$ is the neutron probe error (0.0017 cm$^3$/cm$^3$) and $d_j$ is the depth in millimetres of each of the $M$ soil layers, and $N$ is the number of irrigations. The factor 2 comes from the need for two measurements (before and after each irrigation) to obtain the change in soil water content.

## Results and discussion

The average applied water depths were around 400 and 260 mm in L1 and L2, respectively (Table 3). As a consequence, seasonal ET in L1 was around 100 mm higher than in L2. The seasonal application uniformity, expressed as the Wilkox and Swailes uniformity coefficient (WSUC), was around 90% in C1 and between 67% and 69% in C2 (the corresponding Christiansen uniformity coefficients were around 90% and between 70% and 75%, respectively). The WSUCs averaged for the seven irrigations of the season were somewhat lower (Table 3), showing that seasonal uniformity is greater than that of individual irrigation events.

### Yield and LAI

The average cotton seed yield was 2,349 kg/ha. There were no significant differences among treatments (Table 4). These results contrast with the higher yield obtained for the same cultivar in a previous study at the same location (Mateos et al. 1991a). The late planting and relatively low temperatures early and late in the season limited the heat units of the 1993 cotton season, and thus the yield was below its potential. The same factors may also explain the lack of differences between L1 and L2, i.e. while water availability could have limited yield in the deficit irrigation treatments, temperature was the limiting factor in the

**Table 3** Cumulative and mean Wilcox and Swailes' uniformity coefficient (*WSUC*), total applied water and seasonal evapotranspiration (*ET*) in the four treatment of the experiment. Identification of the treatments as in Table 2. Within a row, values followed by the same letter do not differ at the 0.05 probability level

| Variable | Treatment | | | |
|---|---|---|---|---|
| | L1-C1 | L1-C2 | L2-C1 | L2-C2 |
| WSUC cumulative (%) | 90 a | 67 b | 88 a | 69 b |
| WSUC mean (%) | 83 a | 53 b | 77 a | 51 b |
| Applied water (mm) | 406 a | 396 a | 269 b | 251 b |
| ET (mm) | 886 a | 850 a | 778 b | 747 b |

**Table 4** Cotton seed yield (total, by 22 September and by 9 November), maximum leaf area index (*LAI* on 3 September) and LAI increment during the irrigation season (*ΔLAI*) for the four treatments of the experiment. Identification of the treatments as in Table 2. Within a row, values followed by the same letter do not differ at the 0.05 probability level

| Variable | Treatment | | | |
|---|---|---|---|---|
| | L1-C1 | L1-C2 | L2-C1 | L2-C2 |
| Final yield (kg/ha) | 2,442 a | 2,288 a | 2,215 a | 2,406 a |
| Yield on 22 Sept (kg/ha) | 277 a | 461 a | 873 b | 1,046 b |
| Yield on 9 Nov (kg/ha) | 1,649 a | 1,585 a | 2,037 b | 2,102 b |
| LAI on 3 Sept | 4.4 a | 4.1 a | 2.2 b | 2.3 b |
| ΔLAI (13 Jul–3 Sept) | 3.4 a | 3.0 a | 1.1 b | 1.1 b |

**Table 5** Ratio yield/ET (*Y/ET*), yield/applied water (*Y/AW*), LAI/ET (*LAI/ET*), *LAI/AW* (rainfall plus irrigation from planting to 3 September) and *ΔLAI/AW* (AW = applied water during the 1–6 irrigations) for the four treatments of the experiment. Identification of the treatments as in Table 2. Within a row, values followed by the same letter do not differ at the 0.05 probability level

| Variable | Treatment | | | |
|---|---|---|---|---|
| | L1-C1 | L1-C2 | L2-C1 | L2-C2 |
| Y/ET (kg/ha per mm) | 2.8 a | 2.7 a | 2.8 a | 3.2 b |
| Y/AW (kg/ha per mm) | 6.0 a | 5.8 a | 8.3 b | 9.7 b |
| LAI/ET (1,000/mm) | 6.3 a | 6.1 a | 3.5 b | 3.6 b |
| LAI/AW (1,000/mm) | 12.5 a | 11.6 ab | 9.8 b | 10.1 b |
| ΔLAI/AW (1,000/mm) | 9.2 a | 8.0 a | 4.5 b | 4.8 b |

full irrigation treatment (Orgaz et al. 1992). However, the yield by 22 September and by 9 November were higher in the deficit irrigation than in the full irrigation treatments (Table 4). Similar results have been observed in cotton before (e.g. Mateos et al. 1991a; Orgaz et al. 1992) and attributed to the induction of earliness by water deficit.

Regarding the uniformity factor, yield was not affected by the WSUC difference of 23 points in L1 and 19 points in L2 (Table 4). It seems that the crop characteristics and the weather in the 1993 cotton season imposed little variations in yield for the range of applied water and ET obtained among treatments and within plots of the uniformity treatments (Fig. 2). In other words, uniformity did not reduce yield due to the flat shape of the yield-seasonal ET and yield-applied water functions.

The maximum LAI was affected by the seasonal applied water, giving values above 4 in L1 and below 2.3 in L2 (Table 4). This index was linerly related to seasonal ET (Fig. 3) as it is cotton biomass (Orgaz et al. 1992). Therefore, biomass production was presumably affected by the amount of applied water. In contrast with yield, vegetative growth in L1 was not limited either by water availability or by the seasonal thermal integral. Therefore, according to simulation results of Warrick and Gardner (1983) and Letey et al. (1984), LAI under low uniformity was expected to be lower than LAI under high uniformity, with a higher difference at full irrigation. That trend was observed in the full irrigation treatment of this experiment, both

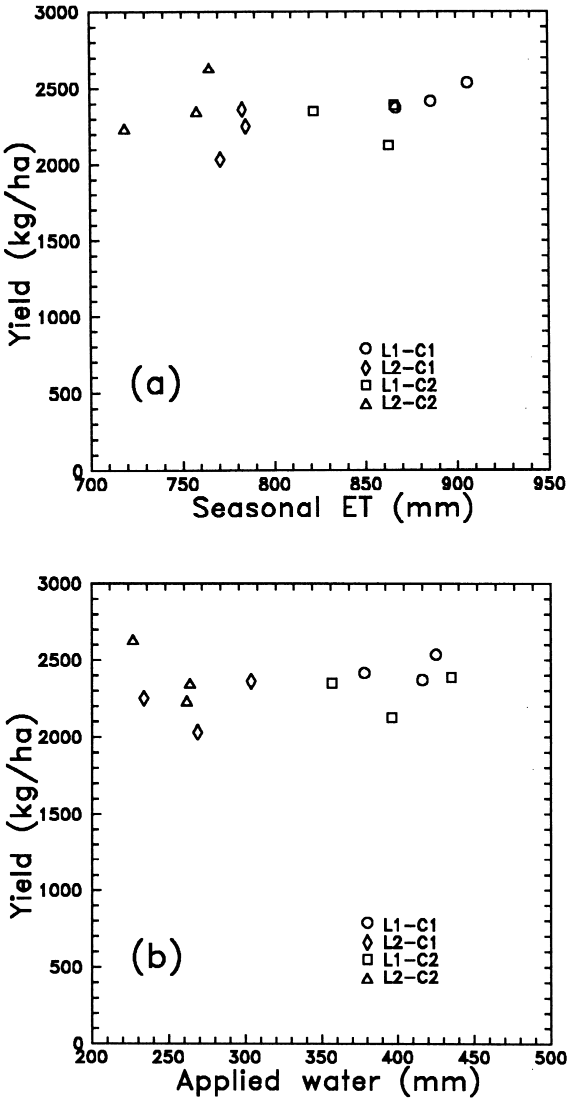


**Fig. 2** Relationship between yield and seasonal evapotranspiration (*ET*) (**a**) and applied water (**b**). Treatment identification as in Table 2

when maximum LAI and the increment of LAI during the irrigation season (ΔLAI) were considered; however, the differences were not statistically significant (Table 4).

## Water use efficiency

The yield and ET results led us to expect a higher water use efficiency (WUE) in the deficit irrigation treatments. This was observed when WUE was expressed as the ratio yield (Y)/applied water (AW) (Table 5). However, WUE expressed as Y/ET was not higher in L2-C1 although it was in L2-C2 (Table 5). The WUE to produce leaf area followed a trend opposite to the WUE for yield. Again, from the models of Warrick and Gardner (1983) and Letey et al. (1984), the ratios LAI/AW or ΔLAI/AW were expected to be higher in L1-C1 than in L1-C2. The trend was observed (Table 5) but the differences were not significant, neither

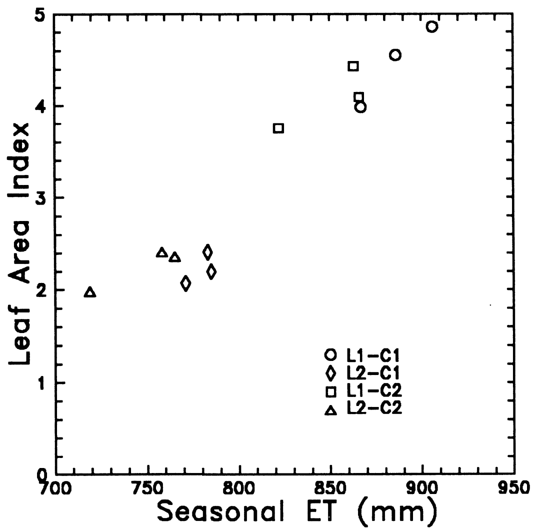


**Fig. 3** Relationship between maximum leaf area index and seasonal ET. Treatment identification as in Table 2

when maximum LAI was referred to AW from planting to the date of LAI measurement nor when $\Delta$LAI was referred to AW in the 1–6 irrigations. Ayars et al. (1991b) also found that WUE improved in their cotton experiment as the uniformity increased, but their experimental design did not allow statistical comparisons.

## Spatial variability of applied water, infiltrated water and ET

As intended, the coefficient of variation of applied water ($CV_{AW}$) was higher in the C2 than in the C1 treatments (Table 6). The coefficient of variation of infiltrated water ($CV_{IW}$) followed the same trend as that of $CV_{AW}$. However, $CV_{IW}$ was always lower than $CV_{AW}$. The coefficient of variation of ET ($CV_{ET}$) was also lower than $CV_{AW}$ and it tended to be lower than $CV_{IW}$ (Table 6). It seems that the water lost by ET in each subplot was close to the water infiltrated, but some infiltrated water was left where excess water was applied and more water initially in the soil was extracted where a water deficit was imposed. In fact, the range of change in the soil water content of the 0.9 to 2.7-m layer was on average, from the beginning to the end of the irrigation season, 60 mm in L1-C2 and 40 mm in L2-C2, with the higher and lower decrements where less and more water was applied, respectively. All this resulted in values of $CV_{ET}$ somewhat lower than values of $CV_{IW}$.

Values of $CV_{IW}$ lower than $CV_{AW}$ may be explained by a damping effect of the soil caused by the horizontal redistribution of applied water through the soil (Hart 1972; Stern and Bresler 1983; Wallach 1990). Ayars et al. (1991b) speculated on this effect when they found that short-scale length of variation resulted in an "apparent" uniformity in terms of plant response, which was greater than the measured value of water application uniformity. In our experiment, the ratio $CV_{IW}/CV_{AW}$ had an average value of 0.36. Somewhat higher ratios were found by Stern and Bresler (1983) in a 12×12 m sprinkler irrigated plot of sweet corn on a soil with 10% clay and 85% sand. However, our 0.36 ratio may include some effect of the cotton canopy on soil water uniformity (Ayars et al. 1991a).

The $CV_{IW}/CV_{AW}$ ratio relates the precipitation uniformity to the effective uniformity after water redistribution. It is similar to the "scalogram" defined by Cogels (1982) and the "$f$" function defined by Seginer (1979) to relate irrigation uniformity to the horizontal extent of the root zone. This type of function may be used to calculate an effective uniformity ($WSUC_e$) on the basis of the WSUC:

$$WSUC_e = (1 - CV_{IW})100 = (1 - f CV_{AW})100 \quad (5)$$

where, in this case, $f = CV_{IW}/CV_{AW}$.

The function $f$ depends on the soil hydraulic characteristics and the scale of variation of precipitation, i.e. the sprinkler spacing. So far, only the experimental approach is available to determine the value of $f$ in other situations.

## Spatial variability of LAI and yield

If root extension was limited to the size of the subplots and water was the only source of variation, the coefficients of variation of LAI and yield should be equal to the coefficient of variation of seasonal ET ($CV_{seas\,ET}$) or, better, to the coefficient of variation of seasonal T ($CV_{seas\,T}$). However, the soil-crop system is characterized by other soil properties subjected to variation (Beckett and Webster 1971) and by the variation in the crop itself. Therefore, $CV_{LAI}$ yielded higher values than $CV_{seas\,ET}$ or $CV_{seas\,T}$ (Table 6), the difference being due to sources of variation other than that of water. Note that $CV_{seas\,T}$ was slightly closer to $CV_{LAI}$ than $CV_{seas\,ET}$ since soil surface evaporation may be higher where LAI is lower. Thus, the variation

**Table 6** Coefficient of variation of applied water ($CV_{AW}$), infiltrated water ($CV_{IW}$), ET during the irrigation season ($CV_{ET}$), LAI ($CV_{LAI}$), yield ($CV_{Yield}$), ET from planting to 3 September ($CV_{seas\,ET}$) and transpiration from planting to 3 September ($CV_{seas\,T}$). Treatment identification as in Table 2. Within a column, values followed by the same letter do not differ at the 0.05 probability level

| Treatment | $CV_{AW}$ | $CV_{IW}$ | $CV_{ET}$ | $CV_{IW}/CV_{AW}$ | $CV_{LAI}$ | $CV_{Yield}$ | $CV_{seas\,ET}$ | $CV_{seas\,T}$ |
|---|---|---|---|---|---|---|---|---|
| L1-C1 | 0.10 a | 0.05 a | 0.04 a | 0.45 a | 0.10 a | 0.13 ab | 0.03 a | 0.04 a |
| L1-C2 | 0.33 b | 0.22 b | 0.13 b | 0.40 a | 0.30 b | 0.18 ab | 0.08 b | 0.13 b |
| L2-C1 | 0.12 a | 0.04 a | 0.02 a | 0.23 a | 0.13 a | 0.10 a | 0.02 a | 0.03 a |
| L2-C2 | 0.31 b | 0.13 c | 0.11 b | 0.37 a | 0.29 b | 0.20 b | 0.07 b | 0.13 b |

of LAI is better explained by the variation of T than by the variation of ET.

It should be pointed out that $CV_{Yield}$ was similar to $CV_{LAI}$ in the high-uniformity treatments while it was smaller in the low-uniformity treatments. Again, the 1993 cotton season allowed the deficiently irrigated plants to open their bolls while the non-deficiently irrigated plants could not open all their bolls, smoothing the yield variation within the plots.

## Conclusions

Uniformity of conventional sprinkler irrigation may not be as important as stated in the literature. For crops with curvilinear crop production functions, such as cotton, low irrigation uniformity does not imply yield reductions. The effect of non-uniformity on vegetative growth seems to be more important but still not significant in the experiment reported here. Although non-uniformity did not reduce yield, it induced variations in vegetative growth and in the time of boll opening. Both phenomena may hinder mechanical harvesting.

On the other hand, the spatial variability of applied water is higher than the spatial variability after water infiltration and redistribution. On average, $CV_{IW}$ was one-third $CV_{AW}$. This effect must be taken into account in agronomic studies of the effects of sprinkler irrigation uniformity on crop yield.

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