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RESPUESTA DEL MAÍZ (*Zea mays* L.) Y SORGO (*Sorghum bicolor* L. Moench) AL RIEGO DEFICITARIO. AGRONOMÍA Y MODELIZACIÓN

MAIZE (*Zea mays* L.) AND SORGHUM (*Sorghum bicolor* L. Moench) RESPONSE TO DEFICIT IRRIGATION. AGRONOMY AND MODELLING

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Als meus pares i germana

RESUMEN

El riego es necesario para asegurar producciones estables en los cultivos de verano en las zonas semiáridas del mundo, donde la precipitación es escasa e irregular. La planificación del uso del agua de riego es crucial para la conservación del recurso y para la sostenibilidad de los sistemas agrícolas. En condiciones de agua de riego limitante, la adopción de estrategias de riego deficitario puede aumentar la eficiencia en el uso del agua.

Esta tesis se centra en el estudio de la respuesta del maíz y el sorgo al riego deficitario. En el capítulo 2 se presenta el estudio comparativo del maíz y el sorgo al riego deficitario impuesto mediante una fuente lineal de aspersión. El objetivo fue el estudio del sorgo como posible cultivo alternativo al maíz bajo condiciones limitantes de agua de riego. Los resultados obtenidos indican que en condiciones de riego óptimo el maíz es más productivo que el sorgo y que el sorgo puede ser una alternativa viable al maíz en condiciones de riego limitante, puesto que presenta menores reducciones de rendimiento.

En el capítulo 3 se plantea el estudio de la respuesta del maíz al riego deficitario aplicado por inundación. Los objetivos de este trabajo fueron: estudiar el efecto de un déficit hídrico moderado en distintas fases del ciclo del cultivo del maíz sobre el crecimiento, el rendimiento y sus componentes. Los resultados obtenidos han indicado que la fase de floración fue la más sensible al déficit hídrico moderado producido por un mayor espaciamiento entre riegos, con reducciones significativas de rendimiento, índice de cosecha y componentes del rendimiento. El riego deficitario en la fase de llenado de grano en ningún caso redujo el rendimiento y sus componentes.

En el capítulo 4 se presentan los resultados de la adaptación, parametrización y validación de un modelo de simulación de cultivos para maíz con datos obtenidos en los ensayos anteriores. El objetivo fue desarrollar una herramienta útil para el análisis posterior de distintas estrategias de riego para las condiciones del Valle del Ebro en España. El modelo predijo de forma satisfactoria la fenología, el crecimiento y el rendimiento en condiciones de agua no limitante y bajo distintos tratamientos de riego deficitario. Se identificaron y discutieron algunas limitaciones del modelo.

ABSTRACT

Irrigation is needed to achieve stable yields in the summer crops of the semiarid regions of the world, where rainfall is scarce and irregularly distributed. Efficient planning of water use for irrigation is crucial for the conservation of the resource and for the sustainability of the agricultural systems. Increase in water use efficiency can be achieved by deficit irrigation practices under water limited conditions.

This thesis focuses on the study of the maize and sorghum responses to deficit irrigation. Chapter 2 presents the comparative study of maize and sorghum to deficit irrigation using the sprinkler line-source technique. The objective was to study sorghum as a possible alternative crop to maize under limited irrigation conditions. The results obtained have shown that maize was more productive than maize under optimum irrigation and that sorghum can be an economically alternative crop to maize if water supply is limited, because of its lower yield reduction under deficit irrigation.

Chapter 3 focuses on the study of maize under deficit flooded irrigation. The objectives were: to study the effect of a moderate water stress at different stages of crop development on crop growth, yield and its components. The results indicate that flowering was the most sensitive phase to the moderate water deficit caused by a greater spacing of the irrigation events, with significant reductions in yield, harvest index and yield components. Deficit irrigation during the grain filling phase had no effect on yield.

Chapter 4 presents the results of a crop simulation model adaptation, parameterization and validation for maize using data from the previous field experiments. The objective was to develop a tool for exploring the consequences for maize yield of different irrigation strategies in the conditions of the Ebro Valley in Spain. The model simulated satisfactorily phenology, growth and yield under no limiting water conditions and under different deficit irrigation treatments. Some model limitations were identified and discussed.

RESUM

El reg és necessari per tal d'assegurar produccions estables dels cultius d'estiu de zones semiàrides del món, on la precipitació és escassa i irregular. La planificació de l'ús de l'aigua de reg és crucial per a la conservació del recurs i per a la sostenibilitat dels sistemes agrícoles. En condicions d'aigua de reg limitant, l'adopció d'estratègies de reg deficitari pot augmentar l'eficiència en l'ús de l'aigua.

Aquesta tesi es centra en l'estudi de la resposta del panís i el sorgo al reg deficitari. Al capítol 2 es presenta l'estudi comparatiu del panís i el sorgo al reg deficitari imposat mitjançant una font lineal d'aspersió. L'objectiu fou l'estudi del sorgo com a possible cultiu alternatiu al panís sota condicions limitants d'aigua de reg. Els resultats obtinguts indiquen que en condicions de reg òptim el panís és més productiu que el sorgo i que el sorgo pot ser una alternativa viable al panís en condicions de reg limitant, donat que presenta menors reduccions de rendiment.

Al capítol 3 es planteja l'estudi de la resposta del panís al reg deficitari aplicat per inundació. Els objectius d'aquest treball foren: estudiar l'efecte d'un dèficit hídric moderat en diferents fases del cicle del cultiu del panís sobre el creixement, el rendiment i els seus components. Els resultats obtinguts han indicat que la fase de floració fou la més sensible al dèficit hídric moderat produït per un interval més gran entre regs, amb reduccions significatives de rendimient, índex de collita i components del rendiment. El reg deficitari durant la fase d'ompliment del gra en cap cas va reduir el rendiment i els seus components.

Al capítol 4 es presenten els resultats de la modificació, parametrització i validació d'un model de simulació de cultius per a panís amb dades obtingudes als assaigs anteriors. L'objectiu fou el de desenvolupar una eina útil per a l'anàlisi posterior de diferents estratègies de reg per a les condicions de la Vall del Ebre a Espanya. El model va predir de manera satisfactòria la fenologia, el creixement i el rendiment en condicions d'aigua no limitant i sota diferents tractaments de reg deficitari. Es van identificar i discutir algunes limitacions del model.

RÉSUMÉ

L'irrigation est nécessaire pour garantir des productions stables des cultures d'été dans les zones semi-arides du monde, où la précipitation est insuffisante et irrégulière. La planification de l'utilisation de l'eau d'irrigation est crucial pour la conservation de ce ressource et pour la durabilité des systèmes agricoles. Dans des conditions limitées d'eau d'irrigation, l'adoption de stratégies d'irrigation déficitaire peut augmenter l'efficience dans l'utilisation de l'eau.

Cette thèse se centre dans l'étude de la réponse du maïs et du sorgho a l'irrigation déficitaire. Dans le chapitre 2 se présente l'étude comparative du maïs et du sorgho à l'irrigation déficitaire imposée en utilisant une source linéaire d'aspersion. L'objectif était l'étude du sorgho comme une possible culture alternative au maïs sous des conditions limitantes d'eau d'irrigation. Les résultats obtenus indiquent qu'aux conditions d'irrigation optimale le maïs est plus productif que le sorgho et que le sorgho peut être une alternative viable au maïs en conditions d'irrigation limitée, puis qu'il présente des réductions du rendement plus faibles.

Dans le chapitre 3 s'étudie la réponse du maïs a l'irrigation par inondation *déficitaire. Les objectifs de ce travail étaient: étudier l'effet d'un déficit hydrique* modéré sur la croissance, le rendement et ses composantes dans des différentes phases du cycle de la culture du maïs. Les résultats obtenus ont indiqué que la phase de la floraison était la plus sensible au déficit hydrique modéré produit par un intervalle plus prolongé de temps entre les irrigations. On a détecté des réductions significatives du rendement, indice de collecte et composantes du rendement. L'irrigation déficitaire dans la phase de remplissement du grain n'a réduit en aucun cas le rendement et ses composantes.

Dans le chapitre 4 se présentent les résultats de la modification, paramètrisation et validation d'un modèle de simulation de cultures pour le maïs avec des données obtenues dans les essais antérieurs. L'objectif était le développement d'un outil pour pouvoir analyser postérieurement des stratégies d'irrigation dans les conditions de la vallée de l'Ebre en Espagne. Le modèle prédit d'une manière satisfaisante la phénologie, le croissance et le rendement sous des conditions de non-limitation d'eau et sous des différents traitements de l'irrigation déficitaire. On a identifié et discuté quelques limitations du modèle.

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INTRODUCCIÓN GENERAL

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INTRODUCCIÓN GENERAL

El agua es uno de los principales factores limitantes para la producción en zonas áridas o semiáridas del mundo, donde la precipitación es escasa y presenta una gran variabilidad intra e interanual. En estas condiciones el riego es fundamental para asegurar producciones elevadas y estables, especialmente en cultivos de verano. En España la superficie de regadío (15% de la superficie cultivada) es responsable del 60% de la producción total agraria (Fereres y Ceña, 1997) y el regadío es el principal usuario de agua. A nivel mundial, más del 80% del agua dulce es utilizada en regadíos (Walker y Skogerboe, 1987; Fereres *et al.*, 1993).

El agua destinada a usos urbanos y otros usos no agrícolas está experimentando una creciente demanda, compitiendo con el regadío por un recurso crecientemente escaso, especialmente en años secos. Las tensiones entre los gestores del agua y los usuarios han aumentado considerablemente en los últimos años, llegándose incluso a cuestionar las regulaciones y leyes de derecho y reparto del agua. La planificación del uso del agua de riego es crucial para la conservación del recurso agua y para la sostenibilidad de los sistemas agrícolas.

El manejo convencional del agua de riego consiste en cubrir las necesidades de los cultivos de forma que se alcancen rendimientos máximos. Sin embargo, cuando el agua es escasa es necesario decidir cómo utilizarla de forma óptima. Entre las posibles estrategias de manejo se citan: riego óptimo de una superficie menor, cambio a cultivos con menores necesidades hídricas o más tolerantes al déficit hídrico y estrategias de riego deficitario. El déficit hídrico en los cultivos es un proceso dinámico y complejo que afecta a numerosos procesos morfofisiológicos (Turner, 1986). El efecto sobre los procesos de crecimiento expansivo y cierre estomático explica en gran medida su impacto sobre la producción de los cultivos. En condiciones limitantes de suministro de agua, es fundamental conocer la relación entre el rendimiento y el agua utilizada en evapotranspiración o en riego (funciones de producción) al objeto de optimizar el uso del agua.

El maíz (*Zea mays* L.) es un importante cultivo de verano en el valle del Ebro, donde ocupa el 19% de la superficie en regadío. Es un cultivo de elevadas necesidades hídricas y que alcanza altos rendimientos cuando el agua y nutrientes no son limitantes. Sin embargo, su alta sensibilidad al déficit hídrico (Stewart *et al.,* 1975; Rhoads y Bennet, 1990), especialmente en floración (Otegui *et al.,* 1995) hace difícil el manejo del agua de riego en condiciones limitantes sin que se produzcan importantes descensos de rendimiento (Lamm *et al.,* 1994).

El sorgo (Sorghum bicolor L. Moench), ocupa el mismo nicho agronómico que el maíz y es considerado un cultivo tolerante a la sequía (Krieg y Lascano, 1990). La capacidad del sorgo de producir rendimientos económicos bajo condiciones limitantes de agua, es debida a su sistema radical muy desarrollado (Wright y Smith, 1983) y a su control de apertura estomática a través del ajuste osmótico (Garrity *et al.,* 1984; Ludlow *et al.,* 1990; Girma y Krieg, 1992).

Debido a sus características, el sorgo podría plantearse como una posible alternativa al maíz bajo condiciones limitantes de agua de riego. Para ello es necesario conocer la respuesta de ambos cultivos al riego. Existen numerosos trabajos en los que se han obtenido las funciones de producción de diferentes cultivos en distintas localidades y condiciones ambientales, evidenciándose que estas relaciones son en general de tipo lineal (Hanks, 1983; Vaux y Pruitt, 1983; Howell, 1990). Sin embargo estas funciones de producción no son únicas para cada cultivo ya que dependen de factores climáticos, edáficos y de manejo del riego. La duración, intensidad y momento del déficit hídrico son factores importantes que determinan el tipo de relación funcional entre el rendimiento y el uso del agua (Hsiao, 1990). La experimentación local es necesaria para conocer los efectos del déficit hídrico en la producción, puesto que la transferibilidad de las funciones de producción de unas zonas a otras es cuestionable.

La realización de ensayos experimentales requiere importantes recursos en tiempo y dinero, y el número de ensayos realizables es limitado. La integración de los procesos que determinan la respuesta de los cultivos al déficit hídrico en modelos de simulación permite reducir el numero de experimentos y aumentar las posibilidades de extrapolación de los resultados. Estos modelos pueden clasificarse de diversas formas atendiendo a su estructura y objetivos. Según su estructura pueden clasificarse en modelos de regresión basados en funciones empíricas o modelos mecanísticos que explican el crecimiento a partir de los distintos procesos fisiológicos. Según los objetivos, pueden diferenciarse los modelos predictivos y los explicativos. Estas clasificaciones no son rígidas y a menudo los modelos contienen elementos de varias categorías. Se han desarrollado numerosos modelos de diferente enfoque y nivel de detalle para distintos cultivos (Jones *et al.*, 1986; van Keulen, 1986; van Keulen and Seligman, 1987; Stockle *et al.,* 1994). El tipo de modelo y el nivel de complejidad más adecuado dependen de los objetivos planteados. Los complejos modelos mecanísticos son útiles para aumentar el conocimiento de los procesos fisiológicos, pero suelen tener una menor aplicabilidad predictiva debido a que exigen cuantificar un elevado número de variables de entrada. Por el contrario, los modelos más simples son a menudo más apropiados para la predicción del rendimiento puesto que requieren menos variables de entrada y son de más fácil uso y aplicación (Boote *et al.,* 1996).

La combinación de la experimentación y de los modelos de simulación de cultivos ha experimentado un notable crecimiento en los últimos años. Se han desarrollado numerosos modelos para condiciones no limitantes de agua y nutrientes. La incorporación de los procesos de crecimiento y producción en modelos que simulen la respuesta de los cultivos al estrés hídrico está menos avanzada. Un modelo de simulación de cultivos, calibrado y validado para las condiciones locales, puede utilizarse como herramienta para estudiar distintas estrategias de riego y mejorar la planificación del uso del agua en condiciones limitantes (Pereira *et al.*, 1995). Además, los modelos permiten localizar áreas de conocimiento limitado y establecer nuevas líneas de experimentación.

Esquema de la tesis

Los resultados experimentales de esta tesis se obtuvieron en ensayos realizados en la finca experimental del Servicio de Investigación Agroalimentaria de Zaragoza en las campañas de 1994, 1995 y 1996.

En el capítulo 2 se presentan los resultados de dos ensayos de maíz y sorgo, realizados con la técnica de la fuente lineal de aspersión (Hanks *et al.*, 1976) en 1994 y 1995. Los objetivos de este trabajo fueron: (i) la comparación de la respuesta del maíz y sorgo al riego deficitario y (ii) la obtención de información respecto a la posible utilización del sorgo como cultivo alternativo al maíz bajo condiciones limitantes de agua en el Nordeste de España.

En el capítulo 3 se presentan los resultados de dos ensayos de maíz bajo riego deficitario por inundación aplicado en distintas fases de su desarrollo en 1995 y 1996. El riego deficitario se produjo aumentando el espaciamiento entre riegos. Los objetivos de este trabajo fueron: (i) estudiar el efecto de un déficit hídrico moderado en distintas fases del ciclo del cultivo del maíz y (ii) obtener información respecto a la adopción de estrategias de riego deficitario por inundación en maíz en una región de alta demanda evaporativa.

En el capítulo 4 se presentan los resultados de la adaptación, parametrización y validación de un modelo de simulación de para maíz con datos obtenidos en los ensayos anteriores. Este trabajo se realizó durante una estancia de 6 meses en el Departamento Theoretical Production Ecology de la Wageningen Agricultural University (Holanda). Se utilizó el modelo LINTUL, que simula el crecimiento a partir de la radiación interceptada y la eficiencia en el uso de la radiación e incluye un submodelo de balance de agua (Spitters and Schapendonk, 1990). El objetivo de este trabajo fue: (i) adaptar, parametrizar y validar el modelo de simulación de cultivos LINTUL y (ii) obtener una herramienta útil para explorar la respuesta productiva del maíz a distintas estrategias de riego en las condiciones del Valle del Ebro en España.

Finalmente, el capítulo 5 presenta las principales conclusiones obtenidas en esta tesis.

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CHAPTER 2

MAIZE AND SORGHUM RESPONSE TO CONTIUOUS DEFICIT IRRIGATION

CHAPTER 2

MAIZE AND SORGHUM RESPONSE TO CONTINUOUS DEFICIT IRRIGATION

Abstract

The growing of more drought tolerant crops can save water in regions where irrigation water is limited. Field experiments were conducted during two growing seasons on a loam soil (Typic Xerofluvent) to compare the responses of maize (*Zea mays L.*) and sorghum (*Sorghum bicolor L. Moench*) to deficit irrigation. Soil water status, crop development, yield and yield components were measured in a sprinkler line-source experiment. Seasonal evapotranspiration, crop growth, total above-ground biomass and yield were markedly affected by the irrigation treatments in both crops. Growth and yield were less in 1994 than in 1995, due to additional salt stress in 1994. Maize was superior to sorghum under well irrigated conditions, but sorghum outyielded maize under moderate or severe water deficits. In both crops yield was reduced through the reduction in the number of seeds per m^{-2} and seed weight. Sorghum had a greater ability to extract soil water from deeper soil and its higher yield under deficit irrigation was achieved by a higher above-ground biomass and a higher HI. Biomass and yield were linearly related to ET in both crops, with absolute greater slopes in maize. The two crops did not differ in WUE but sorghum appeared more efficient in the use of irrigation water (IWUE) under drought. The results show that sorghum could be an alternative crop to maize under limited water supply in the semi-arid conditions of Northeast Spain.

key-words: Maize, sorghum, deficit irrigation, growth, yield, yield components, WUE, IWUE.

1. INTRODUCTION

Since water is a limited resource in many areas of the world and most water is used in agriculture, water conservation in agriculture is needed to extend the use of water for food, fibre and livestock production, as well as for human needs. Different strategies aimed to increase water use efficiency (WUE) in irrigation for the conservation of existing water supplies have been studied in the literature. Among these strategies, the growing of more water efficient crop species or varieties has been considered. In particular, the growing of shorter-season varieties or other crop species capable of producing an acceptable yield under deficit irrigation, have been advocated.

Maize is one of the major summer crops in the Mediterranean region. In the Ebro Valley (Northeast Spain) maize covers 18.6% of the irrigated agricultural land. It is a very water demanding crop and it can give high grain yields (10-12 t ha^{-1}) when water supply and soil fertility are not limiting. However, it is very sensitive to water stress (Stewart *et al.,* 1975; Rhoads and Bennet, 1990) and salt stress (Ayers and Westcott, 1985). It is well known that maize is particularly sensitive to water and other environmental stresses during the period around silking (Robins and Domingo, 1953; NeSmith and Ritchie, 1992a; NeSmith and Ritchie, 1992b; Otegui *et al.,* 1995; Yildirim *et al.,* 1996). The high sensitivity of maize to water stress makes it difficult to implement irrigation management strategies under water limited conditions without incurring considerable loss of yield (Lamm *et al.,* 1994).

In contrast, sorghum has been reported as a crop tolerant to drought (Chaudhuri and Kanemasu, 1982; Krieg and Lascano, 1990) and moderately tolerant to salinity (Maas, 1986). The popularity of the crop in many arid and semi-arid areas of the world stems largely from its ability to yield well under rainfed or water-limited conditions where other summer crops such as maize have consistently failed (Anderson, 1979). Various mechanisms of adaptation which permit sorghum to achieve economic yields under water-limited conditions in comparison with other summer crops have been reported in the literature. The drought resistance of sorghum has been attributed to a dense and prolific root system that is capable of extracting soil water deep in the soil profile (Krieg, 1983; Wright and Smith, 1983; Singh and Singh, 1995), its ability to maintain stomatal opening at low levels of leaf water potential through osmotic adjustment (Jones and Turner, 1978; Garrity *et al.*, 1984; Ludlow *et al.*, 1990; Girma and Krieg, 1992) and its ability to delay reproductive development (Hsiao *et al.*, 1976, Wright *et al.*,1983).

In experiments with deficit irrigation treatments throughout the growing season it can be difficult to separate the effects of water stress from those of salt stress. As the growing season progresses and the soil water is depleted, the concentration of salts in the soil solution may increase, resulting in the consecutive occurrence of drought and salinity. Some studies have indicated that the effect of excess salt is similar to that of water deficiency, with both being expressed through reduced crop water uptake and causing similar plant responses. Both water and salt stress cause a lowering of the total soil water potential, which influences the water status of the leaves. The matric potential (water stress) and the solute potential (salt stress) components have an additive effect in depressing growth and yield (Frenkel *et al.*,1990). However, Shalhevet and Hsiao (1986) found that one unit of water stress was not equal to one unit of salt stress. The more severe effect of water stress was attributed to incomplete osmotic adjustment under drought. Nevertheless, studies on maize (Stewart el al., 1977; Katerji *et al.*, (1998) and other crops (Shalhevet, 1994), revealed that drought and salinity resulted in the same relative reduction in evapotranspiration and yield thus resulting in similar production functions.

Due to its characteristics of drought and salinity tolerance, sorghum appears as a possible alternative crop to maize in dry areas and/or under saline conditions. Maize has proved to be more sensitive than sorghum to both water (Cummins, 1980; Muchow, 1989; Singh and Singh, 1995) and salt stress (Ayers and Westcott, 1985; Nagy *et al.*, 1995).

To assist decisions on crop species in water management strategies, information is needed on the comparative responses to water deficits of possible alternative. The transferability of the crop-water production functions (relationship between yield and water use) among locations has been questioned, since climate, soil, crop management or irrigation practices also determines the functional relation between yield and water use (Hanks, 1983).

In the present study, field experiments were carried out at the same location, in the same years and with the same crop management. The sprinkler line-source technique (Hanks *et al.*, 1976), which provides a variable moisture gradient, was used to characterize the soil moisture extraction patterns, canopy development, crop evapotranspiration, dry matter, grain yield, yield components and their interactions for a maize and a sorghum crop grown in a semiarid environment. The objectives of this study were:

1) to compare the responses of maize and sorghum to deficit irrigation

2) to obtain additional information regarding the adaptation of sorghum as an alternative crop to maize for limited irrigation conditions in the Northeast Spain.

2. MATERIAL AND METHODS

Two field experiments were conducted in Zaragoza, Northeast Spain (latitude 41° 43' N, longitude 0° 49' W, altitude 225 m) during the growing seasons of 1994 and 1995.

2.1. Soil and climate characteristics

The soil, developed from alluvial deposits, was classified as *Typic Xerofluvent, coarse loam, mixed (calcareous), mesic* (SSS, 1992) and is beyond the influence of a water table. The soil physical and chemical characteristics are summarized in Table 2.1. The soil texture is sandy loam in the top soil layer (0-37 cm). Below this layer, the soil texture varies from sandy loam to loam down to a variable depth of 100-120 cm, where a gravel layer occurs. The volumetric moisture content at field capacity (-0.03 MPa) and permanent wilting point (-1.5 MPa) were measured in 20 cm soil layers to 100 cm depth using pressure plates (Richards, 1949). The average volumetric water content at field capacity and permanent wilting point for the 0-100 cm soil profile were 27.8% and 8.9%, respectively. The soil bulk density ranged between 1.30 g cm^{-3} and 1.55 g cm^{-3}. The high values of P and K content in the soil top layer were due to manure application the previous year to the experiments. The most limiting factor for irrigation practices is the low infiltration rate of the topsoil due to its high silt content.

Table 2.1. Soil chemical and physical characteristics of the experimental field.

Hori-zon	Depth (cm)	pH	$EC_{1:5}$ (dS m^{-1})	O.M. (%)	P Olsen (ppm)	K (ppm)	Sand (%)	Silt (%)	Clay (%)
Ap	0-37	8.3	0.39	2.35	50.4	644.6	54.2	32.5	13.3
Bw1	37-53	8.4	0.35	1.10	7.4	268.2	50.6	36.5	12.9
Bw2	53-110	8.5	0.31	0.67	1.1	60.9	55.3	10.7	34.0
2C	110-450	Polygenic gravel							

In 1994 the soil salinity was high as a consequence of field experiments with deficit irrigation carried out during previous years, with water uptake by the crops higher than irrigation and EC of the irrigation water of 2 dS m^{-1}. The electrical conductivity of the 1:5 soil water extract ($EC_{1:5}$) in the top 50 cm soil was measured in November 1994. The electrical conductivity of the soil saturation extract (EC_e) was estimated (Table 2.2) from the $EC_{1:5}$ using the relationship obtained by Isla (1996) in the same plot. The threshold values of EC_e, above which the crop yield is reduced by salinity are 1.7 dS m^{-1} for maize and 6.8 dS m^{-1} for sorghum (Ayers and Westcot, 1985). Salinity levels were found to be well above the threshold values for maize and sorghum (Table 2.2). Consequently both crops had presumably been affected by salts, causing marked reductions in their yields.

During the previous winter to the 1995 experiment, the experimental field was irrigated several times with high irrigation depths to leach salts from the soil and to attain a $EC_{1:5}$ below the threshold values for both crops. $EC_{1:5}$ of the top 30 cm soil was periodically measured during the 1995 growing season to assess a possible build up in soil salinity. In 1995, salinity levels in the experimental field were kept at about 4.00 dS m^{-1} during the growing season (Table 2.2). These values of EC_e were below the threshold value for sorghum in all the irrigation treatments. However, in maize the EC_e was just above the threshold value in T-1 and somewhat above it in the drier treatments.

Table 2.2. Saturation extract electrical conductivity (ECe) in the top 50 cm soil of the maize and sorghum trials. Soil sampling was performed on November the 22nd in 1994 and October the 4th in 1995, respectively.

	ECe (dS m^{-1})			
Treat.	**1994**		**1995**	
	Maize	**Sorghum**	**Maize**	**Sorghum**
T-1	2.68	6.49	2.57	4.74
T-2	6.07	6.60	-	-
T-3	7.65	6.51	3.68	4.68
T-4	8.04	8.43	-	-
T-5	9.07	12.9	5.51	2.79
T-6	-	-	-	-

- Not measured

Fig 2.1 presents daily mean temperature, daily solar radiation and monthly rainfall from May to September of 1994 and 1995, recorded in a weather station located at the experimental site. Temperature and solar radiation patterns did not differ between years. Mean temperature values ranged from 13.0 to 28.7 °C in 1994 and from 11.9 to 29.6 °C in 1995 in the period May-September. In the same period, daily solar radiation values ranged from 2.6 to 30.8 MJ m^{-2} in 1994 and from 7.2 to 30.4 MJ m^{-2} in 1995. Cumulative solar radiation (May-September) was 3509.5 and 3395.5 MJ m^{-2} in 1994 and 1995, respectively. Reference evapotranspiration (ET_0) from sowing to maturity estimated with the Penman-Monteith (Jensen *et al.*, 1990) equation was 713.5 mm in 1994 and 694.5 mm in 1995. Both growing seasons were characterized by rainfall being slightly lower than the average for the region. Total rainfall from sowing to maturity was 40 mm in 1994 and 32 mm in 1995.

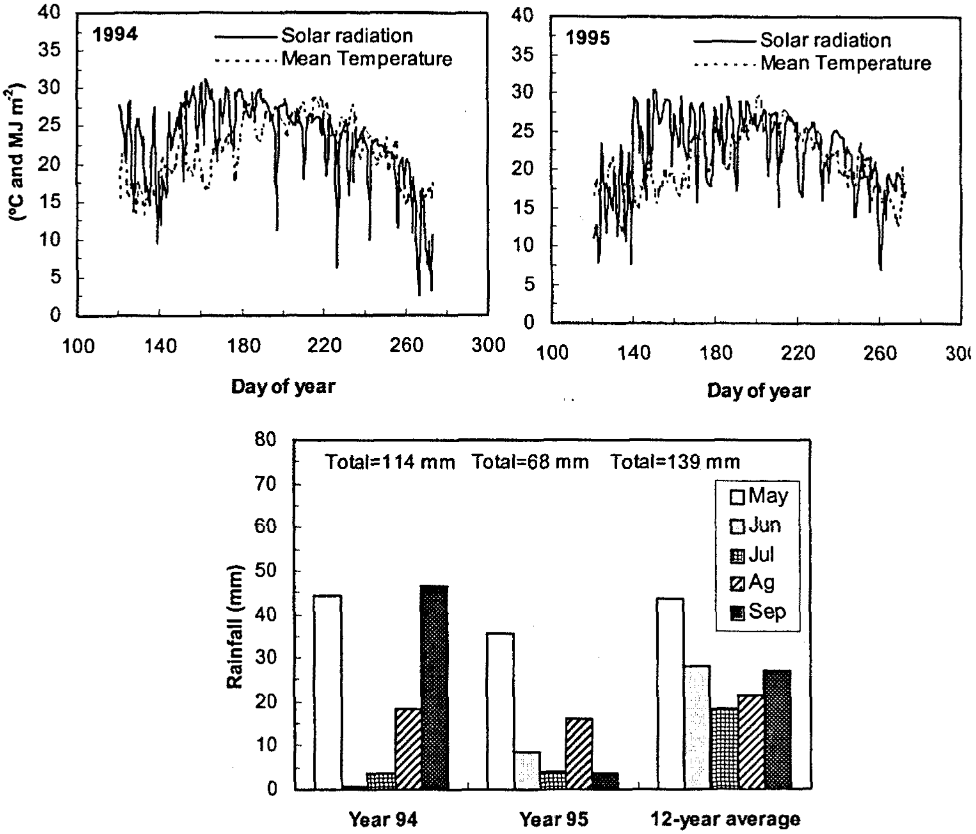

Fig. 2.1. Daily mean temperature and solar radiation from May to September in 1994 and 1995. Monthly rainfall from May to September in 1994, 1995 and 12-year average.

2.2. Irrigation treatments and agronomic details

In 1994 maize (*cv.* Juanita) and sorghum (*cv.* Pioneer 8501) were planted on 19 May. In 1995 maize (*cv.* Prisma) and sorghum (*cv.* Pioneer 8501) were planted on 17 May and 19 May, respectively. Planting date is referred as 0 days after sowing (DAS). Planting was in East-West rows, 0.75 m apart with a plant population in 1994 averaging 7.2 and 20.5 pl m^{-2} in maize and sorghum, respectively. In 1995 plant population was 8.2 and 21.7 pl m^{-2} in maize and sorghum, respectively. Fertilizer amounts were calculated based on soil tests results and expected dry matter production to essentially avoid the influence of these nutrients as production limiting factors. P and K were applied to the plots just before planting. Nitrogen (N) fertilizer was partitioned into one pre-planting application and two post-planting applications. In 1994 maize and sorghum received a total of 280, 240 and 80 kg ha^{-1} of N, P_2O_5 and K_2O, respectively. In 1995 N fertilizer amounts for the different irrigation treatments were estimated based on expected yields. Maize received between 237 and 325 kg/ha of N and sorghum received between 211 and 282 kg ha^{-1} of N. Both crops received 105 kg ha^{-1} P_2O_5 and 105 kg ha^{-1} K_2O. Weeds, pests and diseases were controlled according to normal practices in the area. After flowering a net was placed above the sorghum plot to prevent the crop from birds damage.

The sprinkler line-source technique (Hanks *et al.*, 1976), which provides a continuous variable moisture gradient perpendicular to the sprinkler line, was used to impose the different irrigation treatments. The area covered by the system was 30 m x 72 m, there being 15 m each side of the sprinkler line. Maize and sorghum were grown on both sides of the line source. The line-source, 72 m long with 13 sprinklers 6 m apart, was placed the middle of the plot in east-west direction, producing a decreasing gradient in the amount of water applied at both sides of the line. Sprinkler heads (Model VYR 70) with two nozzles (4.2 mm x 2.4 mm) were operated at 0.4 MPa of pressure, producing a wet radius of 15 m. Maize and sorghum were planted in rows parallel to the sprinkler line. The experimental plot was divided into six water application deficit levels (6 irrigation treatments) each comprising three crop rows on each side of the line source. North and south sides were considered as replicates. The water applied decreased linearly from the line-source (treatment T-1) to the edges of the plot (treatment T-6).

To minimize distortion of the sprinkler pattern, irrigation was applied under calm or light wind conditions (wind speed < 2 m s^{-1}). In 1994 irrigations were applied uniformly to the whole experimental area during the first 39 and 48 DAS in maize and sorghum respectively to help crop emergence and establishment. The total water applied during this period was 100 mm and 130 mm in maize and sorghum respectively. Irrigation using the line-source started 40 and 49 DAS for maize and sorghum, respectively. In 1995 the available soil water provided adequate moisture to achieve a good crop establishment without supplementary irrigation and the differential irrigation treatments with the line-source started 29 and 27 DAS in maize and sorghum, respectively. In both years irrigations were applied in 2 to 4 days intervals, giving a total of 28 and 27 irrigations in 1994 for maize and sorghum, respectively. In 1995 both crops received 27 irrigations. Water applied was measured after each irrigation in 12 catchment cans per crop installed across the experimental plot. Fig. 2.2 shows the cumulative water applied with the line-source for both crops in the 6 treatments at both sides of the line-source. A *t*-test on paired observations indicated that there were no significant differences ($P>0.05$) in the seasonal patterns of applied water between the north and south sides of the line-source in 1994 and 1995 in maize and sorghum. Analysis of variance, performed using the PROC MIXED procedure (SAS, 1996) indicated that there was a significant effect ($P<0.05$) of position on the amount of water applied in both years, indicating an appropriate performance of the sprinkler line-source in these experiments.

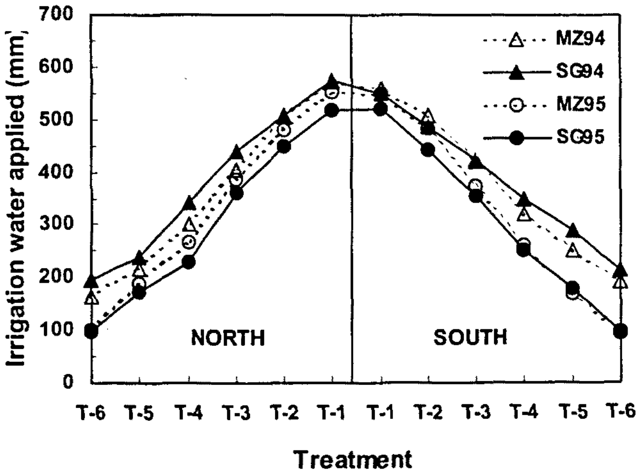

Fig. 2.2. Cumulative amount of irrigation water applied in the different treatments at both sides of the sprinkler line-source for maize (MZ) and sorghum (SG) in 1994 and 1995.

Irrigation scheduling was determined on the basis of the crop evapotranspiration (ETc), which was calculated using the ET_0 of a 12-year average (Faci *et al.*, 1994) and the FAO crop coefficients (Doorenbos and Pruitt, 1977). For simplicity the maize and sorghum crop coefficient values were assumed to be equal. At each irrigation event, irrigation amounts were adjusted (by increasing or decreasing the calculated application amounts) using the current ET_0 data obtained in a grass (*Festuca arundinacea* Schreb) weighing lysimeter located in the same experimental farm. Fig. 2.3 presents the cumulative ETc and the cumulative water applied (irrigation plus rainfall) in T-1 during the growing seasons of 1994 and 1995. The water applied in T-1 was very close to the crop ETc throughout the growing season in both years.

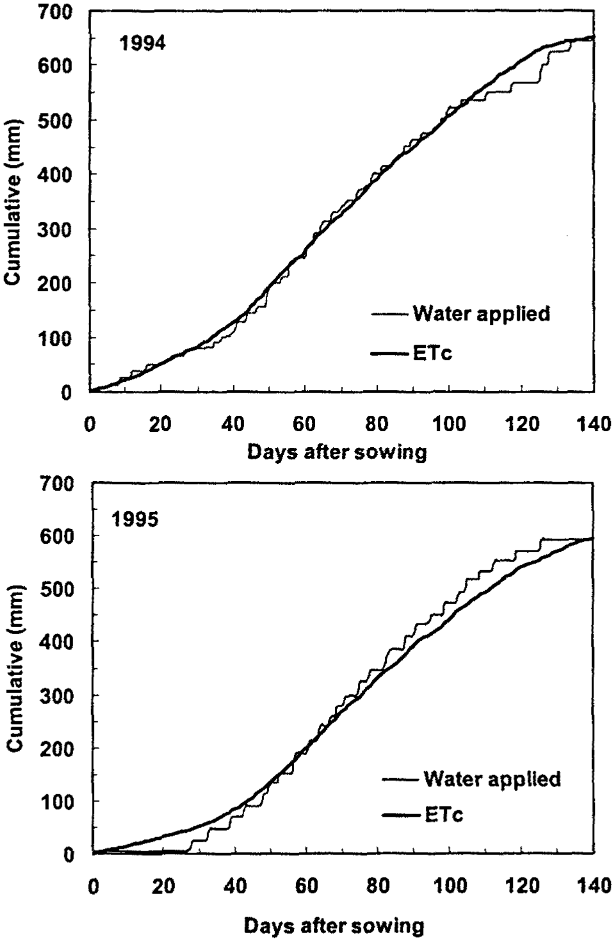

Fig. 2.3. Cumulative crop ET (ETc) and cumulative water applied (irrigation + rainfall) in the well-irrigated treatment (T-1) during the growing seasons of 1994 and 1995. ETc (ETc = $ET_0 \times K_C$).

2.3. Soil water measurements

In 1994 soil water was monitored during the growing season at 10 to 14 day intervals using a neutron probe (Model 3320 Troxler Electronics Laboratories, Inc. North Carolina, USA) calibrated at the experimental field. Readings were taken at 20 cm intervals down to 100 cm in aluminum access tubes (12 tubes per crop) installed at 2.25 m intervals from the sprinkler line to the edges of the plot. In 1995, soil moisture content was measured gravimetrically in two replicates per treatment at sowing and harvest. Volumetric moisture values were obtained from gravimetric contents and bulk density.

Seasonal crop ET in each treatment was estimated from the water balance components: irrigation, rainfall and soil water depletion between sowing and maturity. Runoff was considered negligible since the irrigation events were of short duration: irrigation stopped as soon as flooding of the soil surface was observed. The amount of water applied near the sprinkler line at each irrigation was equivalent to the ETc calculated for the period between consecutive irrigation events. Deep percolation losses were therefore minimized at the sprinkler line and considered to be negligible at locations away from the sprinkler line.

2.4. Plant growth and yield measurements

Phenological events were determined weekly from crop emergence to physiological maturity on each treatment. Phenological stages in maize (Hanway, 1963) and in sorghum (Vanderlip and Reeves, 1972) were recorded when 50% of the plants reached that stage.

Plant height was monitored during the growing season in all the irrigation treatments. Plant height, was taken as the distance from the soil surface to the ligule of the last developed leaf. These measurements were performed on the same 6 to 8 plants of each treatment throughout the season.

Fraction of photosynthetically active radiation intercepted by the crops (fIPAR) was measured every 10 days on average in all the irrigation treatments. fIPAR was calculated from measurements of PAR below and above the crop canopy using a light probe (Sunfleck Ceptometer Dekagon, WA, USA). To minimize the effects of sun angle, measurements were taken at solar noon in cloudless days.

In 1994, leaf area index (LAI) was measured on several occasions during the growing season in T-1, T-3 and T-5 in both crops. In 1995 maximum value of LAI was measured around flowering date. Plant leaf area was obtained as the sum of individual leaf blade areas. Leaf blade area was non-destructively measured as the product blade length x maximum blade width x K_L factor (Norman and Campbell, 1991). The values of the K_L factor for maize (0.74) and sorghum (0.69) were obtained in the 1994 experiment by measuring length, maximum width and leaf blade area of fully expanded leaves (data not shown). Leaf blade area was measured using a leaf-area meter (Area Measurement System Delta T-Devices Ltd., U.K.). NeSmith and Ritchie (1992c) reported a K_L value of 0.75 for maize. Berenguer (1996) found a K_L value of 0.72 on sorghum across a wide range of irrigation treatments.

Above-ground biomass at flowering was obtained by harvesting 2 samples of 1.0 m^2 in maize and 0.5 m^2 in sorghum in each treatment. Plants were separated in leaves (blades plus sheaths), stems and reproductive organs (RO; cobs in maize, panicles in sorghum). Samples were oven dried to constant weight at 70 °C.

After physiological maturity was reached, final harvest was performed in 4 areas of 2.3 to 6.8 m^2 in each treatment. Samples were oven dried to constant weight at 70 °C. Total above ground dry matter, grain yield and yield components were obtained. The harvest index (HI) was determined as the ratio of grain weight to total above ground biomass at maturity. In this work above-ground dry matter and yield data are reported on an oven dried weight basis (oven dried grain had about 6% moisture content).

2.5. Statistical analysis

The sprinkler line-source technique has been widely used in irrigation experiments (Faci, 1986; Cosculluela and Faci, 1990). It has the advantage of providing a high number of irrigation levels with a limited land area and it is simple to operate. Hanks *et al.*, (1980) pointed out that a weakness of the system was that no statistical test was available for the effect of irrigation level on yield because irrigation amounts are applied systematically with no randomization. Hanks *et al.*, (1980) also indicated that since the irrigation effects are usually large, the statistical analysis is not critical, and that caution should be exercised in the interpretation of small differences between adjacent irrigation levels. Later, Johnson *et al.*, (1983) showed how multivariate methods could be used to obtain an appropriate statistical level. The Statistical Analysis System (SAS) has recently presented the PROC MIXED procedure, which allows to obtain a probability level for sprinkler line-source experiments by means of complex matrix calculations (SAS, 1996). Thus, statistical analysis of data and derived variables from the experiments were carried out using the statistical package SAS (SAS, 1996). Procedures used were PROC REG for regressions, PROC MIXED for analysis of variance and MEANS for summarizing data sets.

3. RESULTS AND DISCUSSION

3.1. Soil water depletion

Fig. 2.4 presents the soil water content profiles at the beginning and at the end of the growing season in treatments T-1, T-3 and T-5 in 1994 and 1995 in both crops. The pattern of water depletion with depth as a response to irrigation treatments differed between the two years and crops. Soil water depletion was smaller in 1994 than in 1995.

In 1994, no important differences in soil water depletion were observed between the two crops. In maize, in treatments T-1 and T-3, no significant change in soil water content were found between the beginning and end of the growing season. In sorghum, a small accumulation of water was found in T-1 and no change in T-3. A small water depletion was observed in both crops in treatment T-

5. This small crop water depletion pattern was attributed to the additive effects of water and salt stress. Both stresses had presumably lowered the matric potential (water stress) and the solute potential (salt stress), reducing water uptake by the two crops.

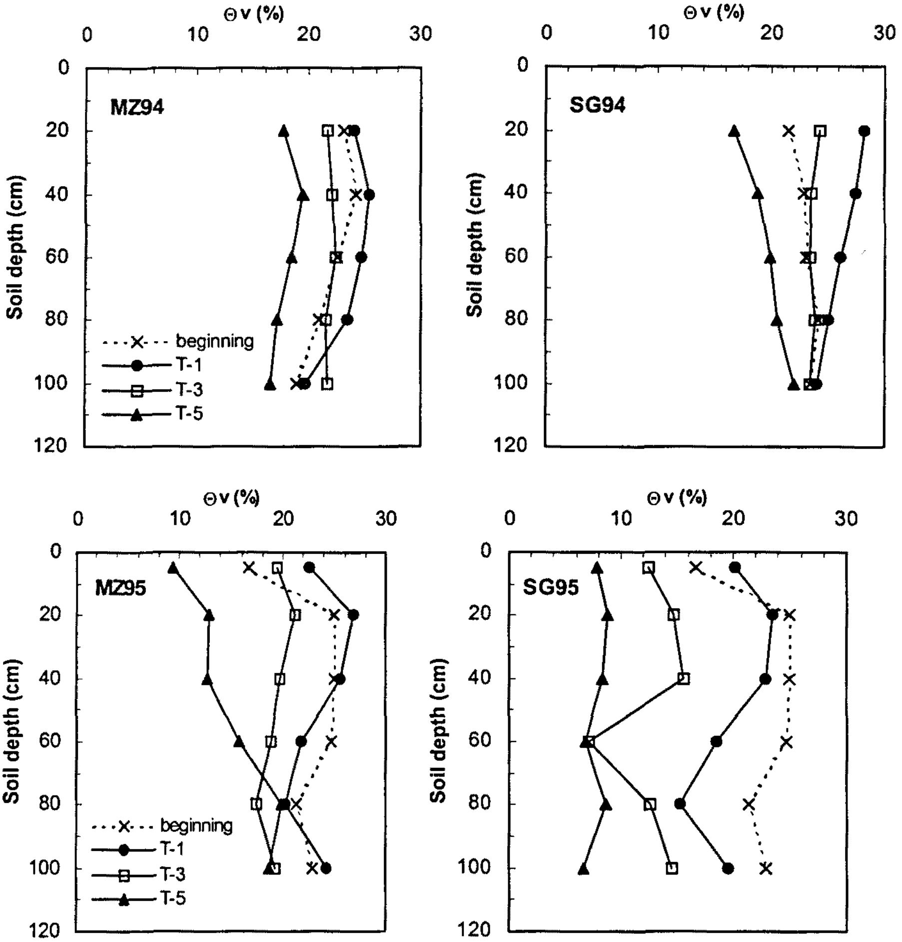

Fig. 2.4. Volumetric water content (θ_v) profiles at the beginning (dashed line) and the end of the growing season (solid line) for treatments T-1 (circles), T-3 (squares) and T-5 (triangles) for maize and sorghum in 1994 and 1995. Each point is the average of two replicates. 1994 data from neutron probe and 1995 data from gravimetric measurements. Water content at the beginning is the average for all the experimental field.

In 1995, soil water depletion in T-1 was relatively small in both crops, although some water extraction from deeper layers (0.5-1.0 m) occurred in both crops, being greater in sorghum than in maize. In T-3 and T-5, sorghum extracted larger amounts of soil water throughout the profile, being the differences between the two crops more important for the drier treatments. As the water stress progressed, the zone of most active uptake in sorghum was gradually shifted down in the profile. In contrast, maize extracted most of the water from the upper layers (0-0.5 m). The partial replenishment of the root zone by light irrigations forced plants to extract relatively more water from the deeper layers in the soil profile. The differences in the soil water extraction patterns between the two crops became more distinct with an increase in water stress (Fig. 2.4). This might be due to differences in the rooting characteristics of the two crops under drought conditions. Sanchez-Díaz and Kramer (1971) reported that sorghum has a more efficient root system because it has twice as many secondary roots per unit of primary roots than maize. For corresponding treatments, soil water content at harvest was lower in sorghum than in maize, indicating that sorghum had a greater capacity to extract water from the soil than maize. Such differences between the two crops were observed in the least irrigated treatments, where sorghum extracted water at higher rates than maize at each depth throughout the profile (below the 0.2 m layer). Singh and Singh (1995) also found that, under limited water supply sorghum extracted more water from the deeper layers (0.5-1.4 m) and maize from the top layers. Gordon *et al.*, (1995) found little water depletion below 90 cm in irrigated and non-irrigated maize grown in a soil of similar available water (17 cm water /90 cm soil).

The effect of water and salinity stress was expressed in 1994 through a reduced water uptake. The 1995 results clearly suggest that under water deficit conditions, sorghum had greater water uptake from the whole soil profile than maize, and that the differences in water uptake were particularly evident at 0.5-1.0 m.

3.2. Water balance components

Water balance components and estimated seasonal ET in all the treatments of maize and sorghum in 1994 and 1995 are shown in Table 2.3. In 1994, the estimated seasonal ET in treatment T-1 (554.0 mm in maize, 581.0 mm in sorghum) was below the potential ETc (651.5 mm) in both crops. In 1995, the estimated ET in T-1 (577.8 mm in maize, 587.9 mm in sorghum) was almost identical to the potential ETc (595.5 mm). The ET was significantly affected by the different irrigation treatments. Seasonal ET from plots receiving varying irrigation amounts ranged from maximum values of 577.8 mm in maize and 587.9 in sorghum (T-1), to minimum values of 234.3 mm in maize and 272.3 mm in sorghum (T-6). In T-1, since soil water depletion was small or negligible, actual ET in both years and crops was close to the water applied (irrigation plus rainfall) (Figure 2.3). In 1995, soil water depletion in T-5 was an important component of the ET, accounting for 44% and 53% of the total seasonal ET in maize and sorghum, respectively.

Seasonal values of maize and sorghum ET were not significantly different between years. However, in 1994, the soil evaporation fraction of the ET was presumably higher than in 1995, due to a lower ground cover, particularly in the drier treatments. Therefore, for analogous values of ET, the crop transpiration component of the ET was assumed lower in 1994 than in 1995. The lower ET values in 1994 could be explained by the high soil salinity level.

Table 2. 3. Water balance components [Irrigation water applied with the sprinkler source line (Irrig) and soil water depletion (SWD)] and estimated seasonal ET in all the irrigation treatments for maize (MZ) and sorghum (SG) in 1994 and 1995. The precipitation amounts from sowing to maturity were 40 and 32 mm in 1994 and 1995, respectively.

		Maize			Sorghum		
	Treat.	**Irrig[1]**	**SWD**	**Seasonal ET[2]**	**Irrig[1]**	**SWD**	**Seasonal ET[2]**
		(mm)	**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**
1994	T-1	433.2	-22.2	**554.0**	431.9	-35.9	**581.0**
	T-2	380.8	-23.5	**500.3**	367.0	-28.9	**523.1**
	T-3	293.7	-7.5	**429.2**	300.7	-6.3	**479.4**
	T-4	198.8	10.9	**352.7**	215.3	16.1	**416.4**
	T-5	127.9	12.5	**283.4**	133.1	35.9	**354.0**
	T-6	75.9	15.6	**234.5**	73.5	13.9	**272.3**
1995	T-1	551.2	-5.5	**577.8**	521.0	35.0	**587.9**
	T-2	481.7	0.9	**514.6**	445.7	66.1	**543.8**
	T-3	379.4	42.8	**454.2**	357.9	113.3	**503.1**
	T-4	263.7	80.4	**376.1**	240.7	155.2	**427.8**
	T-5	179.0	85.5	**296.4**	174.7	168.1	**374.8**
	T-6	98.3	104.0	**234.3**	97.0	145.1	**274.1**

[1] In 1994, Irrig= irrigation water applied from 40 DAS in maize and 50 DAS in sorghum until the end of the season. In 1995, Irrig=total irrigation water applied from sowing until the end of the season.

[2] in 1994 ET for the period sowing-first soil water measurement was estimated in all the treatments as the potential crop ET (120 mm for maize and 162 mm for sorghum) and ET for the rest of the season was estimated from soil water balance. In 1995, seasonal ET was estimated from water balance from sowing to maturity.

3.3. Phenology

In this study, increasing drought stress delayed flowering and maturity of maize and sorghum (Photo 2.1) in both seasons. Drought has been found to either accelerate or delay phenology depending on the crop and the timing and intensity of the water stress. Accelerated phenology has been reported as a common adaptive mechanism to escape from drought in some crops (i.e. chickpea, Johansen *et al.*, 1994; barley, Carberry *et al.*, 1989). Both lengthening and shortening of the growth cycle as a consequence of water deficits has been found in sorghum (Igartua, 1990; Berenguer, 1996). Delayed flowering has often been observed in maize (NeSmith and Ritchie, 1992c; Jama and Ottman, 1993) under water stress conditions.

In 1994, tasseling date in maize ranged between 75 DAS in T-1 and 83 DAS in T-4. In T-5 and T-6 the high degree of water stress prevented maize from flowering. Flowering date in sorghum ranged between 70 DAS for T-1 and 90 DAS for T-6. Maturity date in T-1 was 136 DAS and 103 DAS in maize and sorghum respectively.

In 1995, the mean date of flowering was 73 DAS for maize and 66 DAS for sorghum in T-1, compared to 90 DAS and 77 DAS for maize and sorghum, respectively in T-5. In T-1 the mean time of maturity was 136 DAS and 103 DAS for maize and sorghum, respectively. Maturity was delayed as a consequence of the water stress in both crops. The maturity date was 148 DAS in T-5 in maize (no yield produced in T-6) and 103 DAS in T-6 in sorghum.

In 1994, visual symptoms of salinity were apparent in the maize and sorghum crops during the second half of the growing season. In 1995 salinity symptoms were not discernable, except in the drier treatments of the maize crop.

3.4. Plant height

Plant height was severely affected by the deficit irrigation in both years and crops (Fig. 2.5) (Photos 2.2 to 2.7). Maximum plant height was reached in the treatment T-1 (150.0 cm MZ94; 69.5 cm SG94; 172.6 cm MZ95; 72.4 cm SG95). Plant height reductions in T-3 and T-5 were more marked in 1994 than in 1995, in agreement with the severity of the 1994 water and salt stress. In 1994 the maximum reductions in plant height in the drier treatments were 68% in maize and 54% in sorghum, whereas in 1995 these reductions were 51% in maize and 24% in sorghum. Within a year, plant height was more reduced by stress in maize than in sorghum. Sammis (1988) found plant height and growing degrees day to be a practical tool for predicting the effect of current water management on maize yields reductions up to anthesis if soil moisture stress developed gradually throughout the growing season. As observed previously, plant height was a good measure of the effect of water stress development.

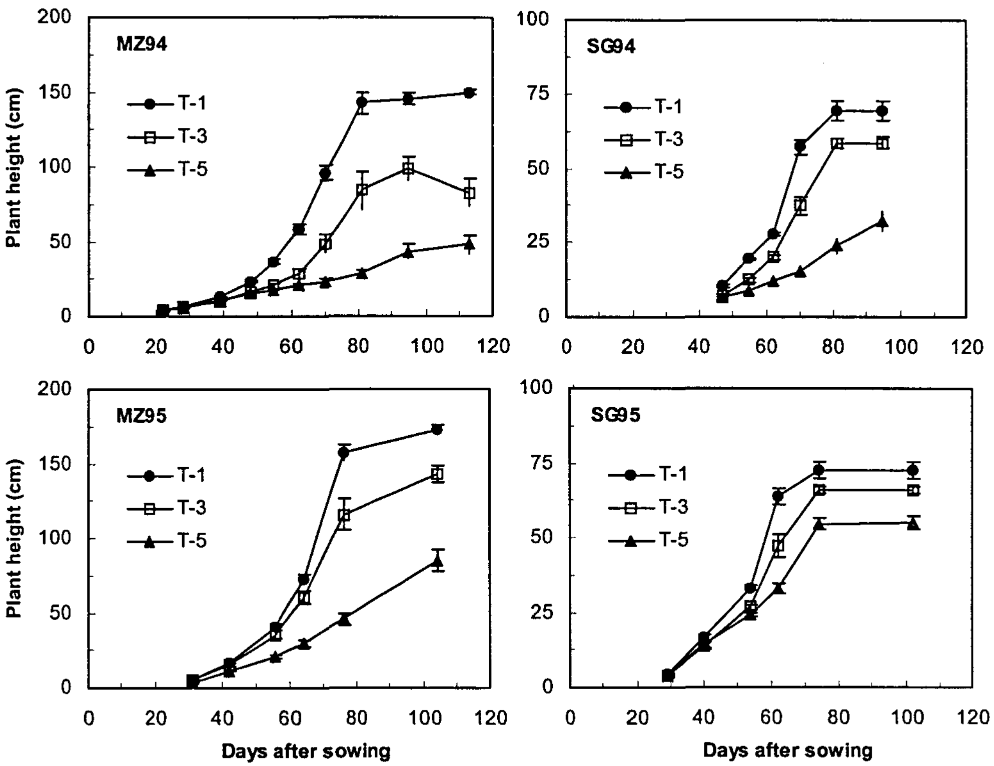

Fig. 2.5. Plant height during the growing season for treatments T-1, T-3 and T-5 in maize (MZ) and sorghum (SG) in the 1994 and 1995 experiments. Each point is the average of 6 to 8 plant measurements. Bars represent standard errors.

3.5. Fraction of intercepted PAR

Vegetative growth was very sensitive to the different irrigation treatments in both years and crops (Photos 2.2 to 2.7). The maximum fraction of intercepted PAR (fIPAR) was reached in all treatments around or shortly after the flowering date (Fig. 2.6). The date of maximum fIPAR was delayed in the water stressed treatments as was phenology. After the maximum fIPAR value was reached, it remained stable until the end of the season. The expected decrease in fIPAR, which might have resulted from leaf senescence was not detected in the measurements, as senescent leaves still standing on the plants were shading the soil.

Photographs

Photo 2.1. General view of the sorghum crop at anthesis stage in rows near the sprinkler line-source (T-1) in 1994.

Photo 2.2. Maize plants of treatment T-1, 83 days after sowing in 1994.

Photo 2.3. Maize plants of treatment T-3, 83 days after sowing in 1994.

Photo 2.4. Maize plants of treatment T-6, 83 days after sowing in 1994.

Photo 2.5. Sorghum plants of treatment T-1, 76 days after sowing in 1994.

Photo 2.6. Sorghum plants of treatment T-3, 76 days after sowing in 1994.

Photo 2.7. Sorghum plants of treatment T-5, 76 days after sowing in 1994.


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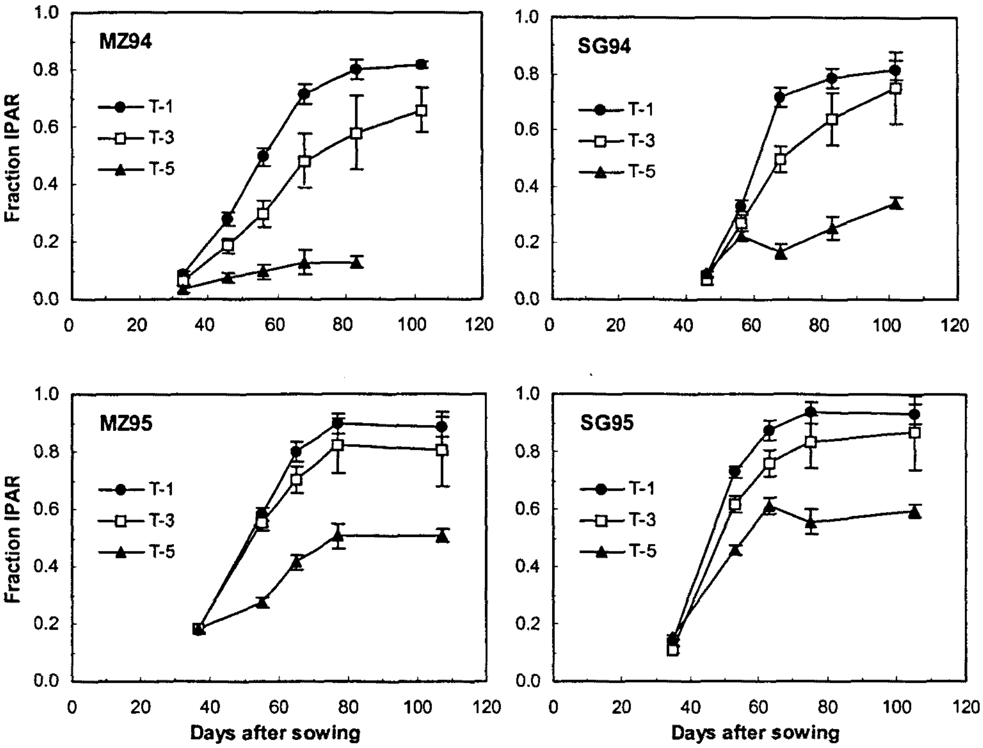


Fig. 2.6. Fraction intercepted PAR (fIPAR) during the growing season for treatments T-1, T-3 and T-5 in maize (MZ) and sorghum (SG) in the 1994 and 1995 experiments. Each point is the average of two measurements per treatment. Bars represent standard errors.

The general trend of fIPAR reduction as irrigation level decreased was observed in both years and crops. The largest values of fIPAR were achieved in T-1 (0.80 MZ94; 0.89 SG94; 0.91 MZ95; 0.93 SG95). Except for the low value of fIPAR observed in MZ94, these values are in agreement with those found by Maddonni and Otegui (1996) in maize (0.90) and Rosenthal *et al.*, (1985) in sorghum (0.90).

As observed for plant height, the reductions in maximum fIPAR in T-5 were greater in 1994 than in 1995 (84% MZ94; 56% SG94; 43% MZ95; 38% SG95) being greater for maize than for sorghum.

3.6. Leaf area and canopy architecture

In all treatments maximum LAI (Table 2.4) was reached around or shortly after flowering. At that time the fraction of intercepted PAR was near maximum but still increasing somewhat in all treatments. LAI was markedly less in 1994 than 1995, but in both years and crops a decrease in leaf area was observed with increasing irrigation deficit. LAI in the drier treatments showed greater reductions (respect T-1) in 1994 (76% in maize, 70% in sorghum) than in 1995 (61% in maize, 26% in sorghum). In 1995, LAI of maize was reduced more than sorghum in response to deficit irrigation (Photos 2.8, 2.9 and 2.10).

Table 2. 4. Maximum leaf area index (LAI) and light extinction coefficient (K) at flowering stage in T-1, T-3 and T-5 in both years and for both crops. K was estimated from LAI and intercepted PAR measurements using Beer's Law.

Year	Treat.	LAI[1] ($m^2\ m^{-2}$)		K	
		Maize	Sorghum	Maize	Sorghum
1994	T-1	3.53 (0.08)	3.72 (0.19)	0.45	0.37
	T-3	2.14 (0.15)	3.60 (0.20)	0.40	0.24
	T-5	0.86 (0.33)	1.13 (0.25)	0.16	0.25
1995	T-1	5.04 (0.07)	6.36 (0.84)	0.46	0.42
	T-3	4.64 (0.15)	4.89 (0.74)	0.37	0.32
	T-5	1.95 (0.45)	4.73 (0.68)	n.d.	0.17

[1] Values between brackets are Standard Error of the LAI means (SE). In 1994 n=6; In 1995 n=5.
n.d. = data not available

In 1994, within the range of measured LAI (< 4) and for the set of data across time and irrigation treatments, a linear model best fitted the relationship between LAI and fIPAR for both crops (Fig. 2.7). The greater slope of the sorghum regression indicated differences in leaf architecture between crops. The light extinction coefficient (K) was estimated for each crop from LAI and fIPAR measurements using Beer's Law (fIPAR = 1- exp (-K x LAI)). In both years, estimated K at flowering (Table 2.4) indicated differences in leaf architecture, both under well-irrigated (T-1) and under water deficit conditions (T-5). In T-1, K at flowering was greater for maize than for sorghum, due to the more vertical leaf disposition in sorghum than in maize. Flenet *et al.*, (1996) reported similar values of K for maize (0.44) and sorghum (0.36) grown at row spacing of 0.7 m under no water limitation. In T-5, K was lower in maize than in sorghum, due to greater leaf rolling in maize as a response to water deficit. The average K across the 1994 season and treatments was higher in maize (0.44) than in sorghum (0.32).

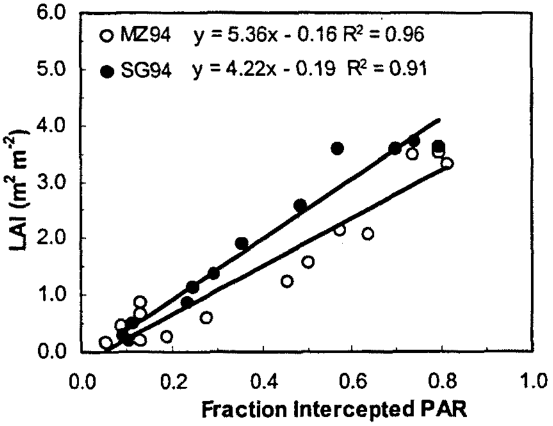


Fig. 2.7. Relationship between leaf area index (LAI) and fraction intercepted PAR for maize and sorghum in 1994.

Species have different mechanisms for reducing effective leaf surface and thus decreasing radiation interception when suffering from drought. Among them, changes in leaf angle or leaf rolling have been reported in maize and sorghum varieties. K is a measure of how canopy structure and orientation influence the efficiency with which a given leaf area intercepts radiation, although important genotypic variations have been observed in K (Matthews *et al.*, 1990). Changes in K can be brought either by changes in leaf angle or by leaf rolling. In this study, leaf-rolling and more erect leaves were observed in both crops in the central hours of the day in the drier treatments (data not shown). Under drought conditions, leaf-rolling in maize contributed more to changes in K than erect leaf disposition, whereas the reverse was true for sorghum.

Photographs

Photo 2.8. General view of the maize crop in the sprinkler line-source experiment at 79 days after sowing in 1994.

Photo 2.9. View of the maize crop across the experimental plot. Plants in the background are near the sprinkler line-source (T-1) and plants in the foreground are in the drier treatments (T-6).

Photo 2.10. General view of the sorghum crop at maturity. Net placed above the sorghum plot to prevent the crop from birds damage.

2.8

2.9

2.10

3.7. Dry matter partitioning

The total above-ground dry matter (DM) at flowering was less in the drier treatments and was significantly lower in 1994 than in 1995 for both crops (Fig. 2.8). The reduction in DM in T-5 respect to T-1 was greater in 1994 (90% in maize and 82% in sorghum) than in 1995 (61% in maize and 31% in sorghum), which may be due to the salt stress in 1994. Within a given year the reduction in DM was greater in maize than in sorghum.

In 1994 DM samples were taken 77 DAS in both crops, corresponding to the date of silking in T-1 of maize, and 7 to 10 days after flowering in sorghum. For this reason, at 77 DAS the contribution of reproductive organs (RO) to DM was greater in sorghum than in maize. In T-1, DM was similar for both crops, but in T-3 and T-5 it was greater in sorghum. This results showed that in the period up to flowering maize was more sensitive to water and salt stress than sorghum.

In 1995 DM samples were taken 79 DAS in maize and 68 DAS in sorghum, corresponding to approximately the date of flowering of T-1 in both crops. No significant differences in DM were found between maize and sorghum in T-1 and T-3. However, sorghum had higher DM than maize in T-5, showing maize greater sensitivity than sorghum to deficit irrigation.

The amount of applied water greatly affected the patterns of dry-matter accumulation in both years. The distribution of total DM in the different plant parts (leaves, stems and RO) differed significantly among treatments. In 1994, at flowering in maize, the contribution of leaves to total DM was 53%, 59% and 96% in T-1, T-3 and T-5, respectively, whereas in sorghum this contribution was 23%, 19% and 12% in the same treatments. In 1995 the contribution of leaves to total DM in maize was 49%, 52% and 64% in T-1, T-3 and T-5, respectively, whereas in sorghum it was 54%, 58% and 75%, respectively in the same treatments.

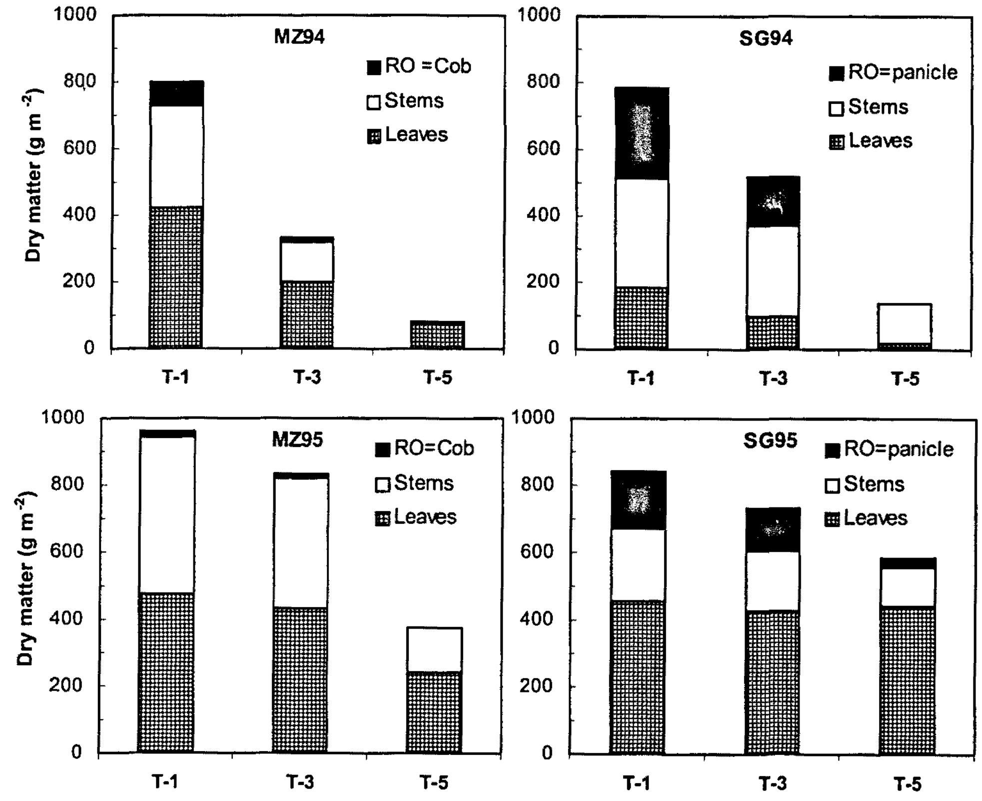


Fig. 2.8. Above-ground dry matter (DM) and its partitioning in leaves, stems and reproductive organs (RO; cobs in maize and panicles in sorghum) for treatments T-1, T-3 and T-5 around flowering stages in 1994 and 1995. Dates of sampling were 77 DAS in MZ94, 77 DAS in SG94; 79 DAS in MZ95; 68 DAS in SG95.

The greater reduction of total above-ground DM found in 1994 was attributed to the additive effects of water and salt stress. The greater reduction in maize confirmed the better performance of sorghum under drought and salinity conditions found previously in a similar environment (Nagy *et al.*, 1995)

3.8. Above-ground dry mater, yield and harvest index

Above-ground dry matter (DM) and grain yield at harvest resulted severely affected by the decreasing amounts of irrigation applied in both years and crops (Table 2.5). DM and yield were significantly different between years. For the same treatment, DM and yield of maize and sorghum were less in 1994 than in 1995, due to the effects of water and salt stress in 1994.

Table 2.5. Above-ground dry matter (DM), grain yield and harvest index (HI) for the different irrigation treatments in maize and sorghum in 1994 and 1995. Data are expressed as oven-dried biomass.

Year	Treat.	DM (g m^{-2})		Yield (g m^{-2})		HI	
		Maize	Sorghum	Maize	Sorghum	Maize	Sorghum
1994	T-1	1591.4	1196.6	694.4	622.3	0.44	0.52
	T-2	966.7	1137.1	358.9	604.2	0.36	0.53
	T-3	979.5	897.7	348.8	426.1	0.34	0.47
	T-4	453.6	508.8	82.7	175.4	0.17	0.34
	T-5	161.4	301.4	0.0	37.6	0.00	0.12
	T-6	66.7	153.7	0.0	10.2	0.00	0.06
1995	T-1	2140.1	1837.7	1082.2	853.8	0.51	0.49
	T-2	1740.6	1638.3	878.8	741.8	0.50	0.47
	T-3	1099.8	1299.8	480.1	629.5	0.43	0.46
	T-4	700.3	1072.7	195.1	488.5	0.28	0.46
	T-5	485.1	728.4	55.8	265.1	0.12	0.37
	T-6	356.6	522.3	9.5	64.3	0.03	0.13

In 1994, in T-1, maize had a greater above-ground DM (1591.4 g m^{-2}) and yield (694.4 g m^{-2}) than sorghum (1196.6 g m^{-2} of DM and 622.3 g m^{-2} of yield). However, sorghum was more productive than maize under a wide range of deficit irrigation treatments (T-2 to T-6).

In 1995, maize outyielded sorghum in the most irrigated treatments (T-1 and T-2), but water deficits reduced yields in maize more than in sorghum, and sorghum yielded more than maize in the drier treatments (T-3 to T-6). In T-1, maize produced more DM (2140 g m^{-2}) and grain yield (1082 g m^{-2}) than sorghum (1838 g m^{-2} of DM and 854 g m^{-2} of yield). In both years the effects of the deficit irrigation on yield were greater than on DM production, as reflected in the lower harvest index (HI) under deficit irrigation. The reduction in HI consequent on irrigation deficit was greater in 1994 than in 1995 and within each year was greater in maize than in sorghum. In maize, the proportion of DM partitioned to the grain (HI) was reduced over a wide range of deficit irrigation. In contrast, in sorghum there was a range of deficit irrigation over which the HI was unaffected, but the HI was severely reduced at large irrigation deficits. Similarly, with sorghum, Garrity *et al.* (1983) reported no change in HI for a range of water deficits. Faci and Fereres (1980) found HI reductions, but less than those found in this study, in a sorghum experiment using the sprinkler line-source. The results of this work confirmed those reported by Sullivan *et al.* (1980) and Muchow (1989) that maize yielded more than sorghum in high-yielding environments, but with increasing water deficit sorghum outyielded maize.

3.9. Yield components

Table 2.6 shows the yield components: number of reproductive organs per square meter (RON m^{-2}), kernel number per RO (KN RO^{-1}), kernel weight (KW), and kernel number per square meter (KN m^{-2}) for maize and sorghum in the 1995 experiment. All yield components decreased to some extent by the deficit irrigation treatments.

Table 2.6. Effect of irrigation treatments on yield components for maize and sorghum in 1995. Reproductive organ (RO; cob in maize, panicle in sorghum). Number of RO per square meter (RON m^{-2}), kernel number per RO (KN RO^{-1}), kernel weight (KW) and kernel number per square meter (KN m^{-2}).

Treat	RON m^{-2} (a)		KN RO^{-1} (b)		KW (mg) (c)		KN m^{-2} (a x b)	
	Maize	Sorghum	Maize	Sorghum	Maize	Sorghum	Maize	Sorghum
T-1	7.9	21.3	472.6	1543.4	291.1	26.1	3722.7	32777.0
T-2	7.6	20.5	406.3	1485.8	284.4	24.6	3079.3	30259.0
T-3	7.0	18.7	284.1	1336.8	241.6	25.2	1973.5	24960.0
T-4	4.4	17.0	199.5	1203.3	220.4	24.0	888.1	20353.0
T-5	1.9	16.3	136.9	782.0	203.5	20.8	275.3	12711.0
T-6	0.5	9.6	108.9	409.0	185.5	16.0	45.6	3979.0

Table 2.7 presents the reduction in yield, KW and KN m^{-2} relative to the T-1 treatment for maize and sorghum. For analogous treatments, reductions in yield were higher in maize than in sorghum (Photos 2.11 to 2.15), and increased as the water-applied decreased, ranging from 13% in maize and 18% in sorghum in T-2 to 99% in maize and 92% in sorghum in T-6. The maximum yield reductions found here were higher than those reported by Garrity *et al.*, (1982a) for a different sorghum variety in a line-source experiment (25-45% yield reduction).

Table 2.7. Reductions (relative to full irrigation treatment for each crop) for yield, kernel weight (KW) and kernel number per square meter (KN m^{-2}) in the different irrigation treatments in maize and sorghum in 1995.

Year	Treat.	Yield reduction (%)		KW reduction (%)		KN m^{-2} reduction (%)	
		Maize	Sorghum	Maize	Sorghum	Maize	Sorghum
1995	T-1	0.0	0.0	0.0	0.0	0.00	0.0
	T-2	18.8	13.1	2.3	5.9	17.3	7.7
	T-3	55.6	26.3	17.0	3.4	47.0	23.9
	T-4	82.0	42.8	24.3	8.1	76.1	37.9
	T-5	94.8	69.0	30.1	20.4	92.6	61.2
	T-6	99.1	92.5	36.3	38.7	98.8	87.9

Grain yield is the product of KN m^{-2} and KW. As observed previously (Kiniry and Ritchie, 1985; Saeed *et al.*, 1986; Bolaños and Edmeades, 1993; Otegui and Bonhomme, 1998) KN m^{-2} was the major contributing component of yield variation in both crops, with little change in KW despite large differences in yield. KN m^{-2} accounted for 99% of the yield variation in maize and sorghum (Fig. 2.9).

Photographs

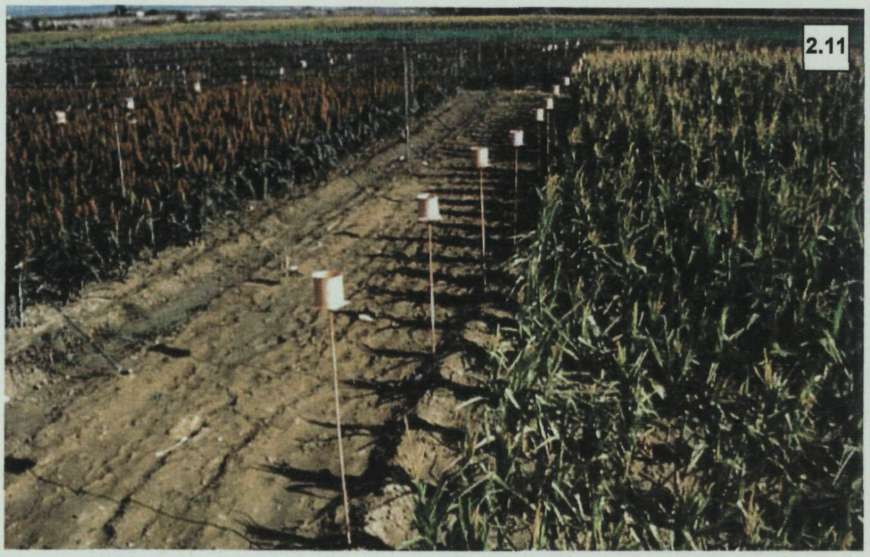
Photo 2.11. General view of the maize and sorghum experiment in 1995. Passage between the crops and raingauge lines.

Photo 2.12. Sorghum panicle at anthesis in the full-irrigated treatment (T-1).

Photo 2.13. Sorghum panicle at milk stage in the full-irrigated treatment (T-1).

Photo 2.14. Sorghum panicle at physiological maturity in the full-irrigated treatment (T-1).

Photo 2.15. Representative maize ears of treatments T-1, T-2, T-3, T-4 and T-5 at harvest in 1995.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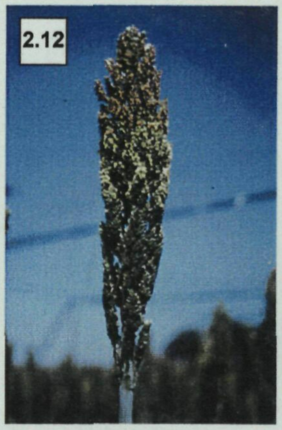
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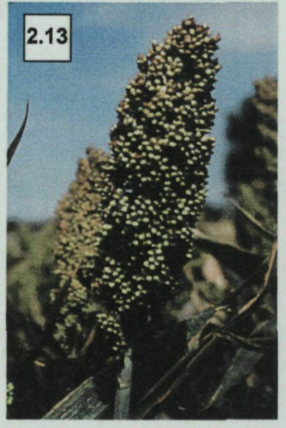
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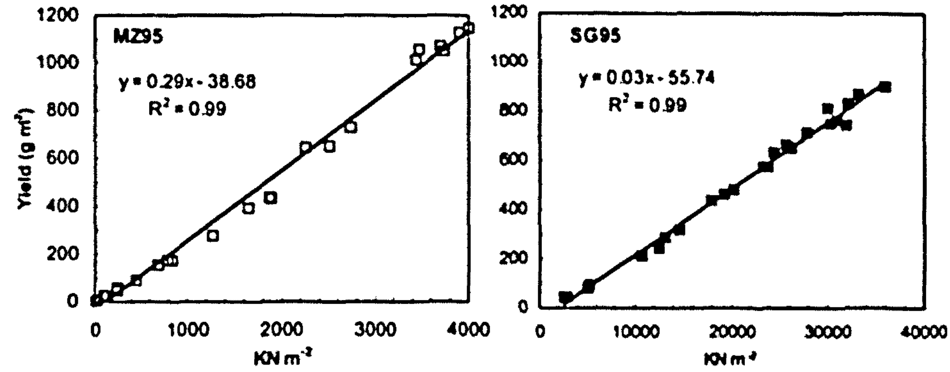

Fig. 2.9. Grain yield as a function of kernel number per square meter (KN m^{-2}) for maize and sorghum in 1995. Data obtained at final harvest in all the irrigation treatments.

The reductions in KN m^{-2} (maximum reductions of 99% in MZ95 and 88% in SG95) were due to both reductions in number of RO per square meter (RO m^{-2}) and in number of kernels per RO. The RO m^{-2} is the first phenological component affected by water stress and was more reduced in MZ95 (4-94%) than in SG95 (4-55%). The reduction in the number of kernels per RO was similar in MZ95 (14-77%) than in SG95 (4-74%). Kernel weight, which is established later than KN during the cycle is the result of kernel growth during the grain filling period (Maddonni *et al.*, 1998). In this work KW was also affected by the water deficit but to a lesser degree than the other yield components (maximum reductions of 36% in MZ95 and 39% in SG95). The greater reduction in KN m^{-2} than in KW found in both crops, indicated that the water deficit that occurred around silking (kernel set determination) was more detrimental for yield than the water deficit that occurred during the grain filling period (kernel weight determination). Similarly, other authors have reported greater reduction in kernel number than in kernel weight for maize (Bolaños and Edmeades, 1993; Otegui *et al.*, 1995) and for sorghum (Saeed *et al.*, 1986; Mastrorilli *et al.*, 1995; Berenguer and Faci, 1997) in response to drought.

Some grain crops have shown an important yield compensation capacity under water deficits occurring during a part of the growing season (Begg and

Turner, 1976). For example, Kumar *et al.*, (1994) in indian mustard found that water stress reduced the number of seeds per plant, but final yield was partially compensated by larger seeds. In sorghum (Wright *et al.*, 1983; Manjuarez-Sandoval *et al.*, 1989) and in maize (Eck, 1986) some compensation in kernel weight has been found in some cases where seed number was reduced by water deficits during the vegetative stage. In the present study, the moisture gradient provided by the sprinkler line-source caused a gradual buildup of stress over the entire growing season. Under this progressive water deficit, all the yield components were affected and no yield compensation was observed either in maize or in sorghum.

3.10. Yield responses to seasonal ET

The relationship between seasonal ET and yield for both crops in both years is presented in Fig. 2.10. The range in ET between the various irrigation treatments was similar in both years. However, the grain production at any level of ET was greater in 1995 than in 1994. Grain yield showed a linear response to ET. In 1994 a single linear regression was fit to the data set, since no significant differences were found between the maize and the sorghum ET-Y regressions. In 1995, the ET-Y relationships were significantly different for maize and sorghum, being the slope of the relationship greater in maize than in sorghum, indicating a higher sensitivity to ET deficit for maize than for sorghum.

A linear model was the best fit to describe the ET-Y relationships for both crops in both seasons (Fig. 2.10). Logistic relationships did not significantly improve the fitting. Although some authors have reported sigmoid relationships, most of the studies have shown linear ET-Y relationships for maize and sorghum (Stewart *et al.*, 1975; Garrity *et al.*, 1982b; Howell, 1990; Tolk *et al.*, 1997) among other crops. However, considerable variation has been found both in the slope of the relationship and in the point at which yield reduction becomes 100%. Apart from crop characteristics and sensitive stages, factors such as climate, soil properties, irrigation practices and other growth factors affect the relationship between ET and yield (Hsiao, 1990). In this study, the ET-Y relationships differed more between the two years than between the two crops within a given year.

Similarly, Retta and Hanks (1980) found more differences between years than between crops when comparing maize and alfalfa in different years. Faci and Fereres (1980) found different slopes in the ET-Y relationship for sorghum grown under different irrigation frequencies.

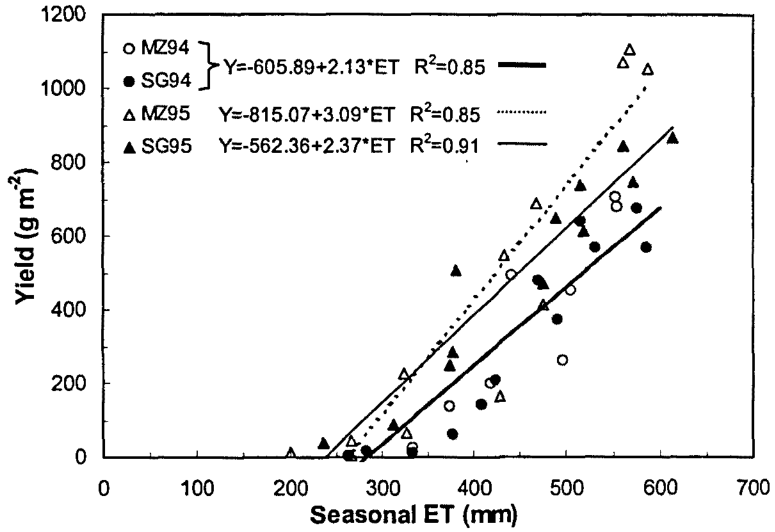

Fig. 2.10. Relationship between grain yield (Y) and seasonal estimated ET (ET) for maize (MZ) and sorghum (SG) in 1994 and 1995. A single regression was fitted to the whole set of data in 1994, since there were no significant differences in the Y-ET relationship between the crops.

3.11. Yield responses to irrigation

The relationships between grain yield and net water applied for the two crops in the two growing seasons are shown in Fig. 2.11. Net water application refers to the amount of water actually reaching the top of the canopy as measured by catch gauges, as opposed to the gross amounts applied by the sprinkler system.

In addition to the conceptual relevance of obtaining the Y-ET relationships, knowledge of the relations between yield and irrigation (I) is economically crucial. Since not all irrigation water is used in the ET processes (for example, runoff, deep percolation) and a fraction of the ET comes from sources other than irrigation (stored soil water, rainfall), the knowledge of the Y-I relationships is essential for the efficient use of irrigation water.

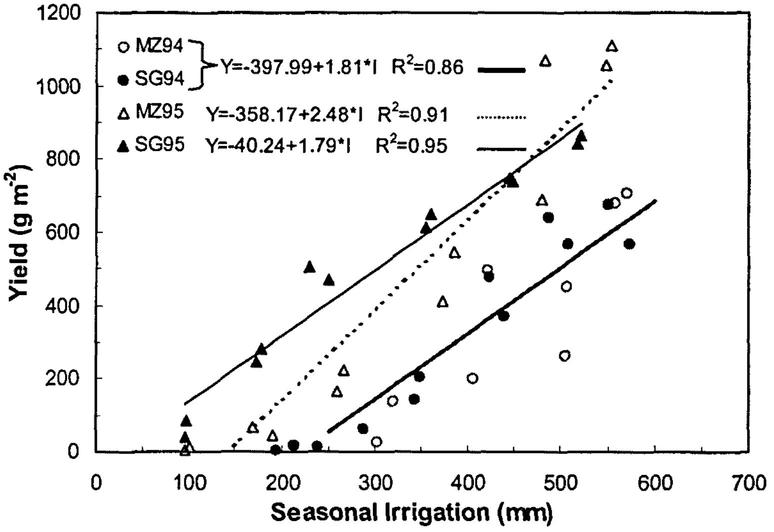

Fig. 2.11. Relationship between grain yield (Y) and seasonal irrigation applied (I) for maize (MZ) and sorghum (SG) in 1994 and 1995. A single regression was fitted to the whole set of data in 1994, since there were no significant differences in the Y-I relationship between the crops.

No linear relations between yield and irrigation had been reported at high irrigation levels and at low irrigation uniformity (Mantovanni *et al.*, 1995). However, Garrity *et al.*, (1982a) observed yield to be linearly related to seasonal water applied for different sorghum cultivars. In this study, within the range of seasonal irrigation water applied (I), a linear model best fitted the Y-I relationships. The Y-I relationships differed significantly between years. In 1994, maize and sorghum yields responded similarly to irrigation, and thus a single linear regression was fit to the data set. In 1995, important differences were found in their yield responses to irrigation amounts. Maize outyielded sorghum at the highest level of water applied, but the slope of the relationship was greater for maize, sorghum yields being greater than those of maize over a wide range irrigation amounts applied. The cross-over point below which sorghum outyielded maize was 460 mm of net water application, corresponding to a grain yield of 783 g m^{-2}.

3.12. Harvest index

A linear-constant value model was fitted to the relationship between harvest index (HI) and both ET and seasonal irrigation amount (I) (Fig. 2.12). HI increased linearly with ET and I until a certain threshold value and then was kept stable for a range of high ET and I values in both crops and years. In 1994 the threshold value of HI was greater in sorghum than in maize for both the HI-ET and the HI-I relationships and the reverse was true in 1995. In 1995 maize had greater HI than sorghum at high ET and I levels, but the HI was kept stable for a wider range of ET and I deficit than maize. The differences between years were attributed to the more deleterious effects of water and salt stress in the fraction of dry matter partitioned into grain yield in 1994.

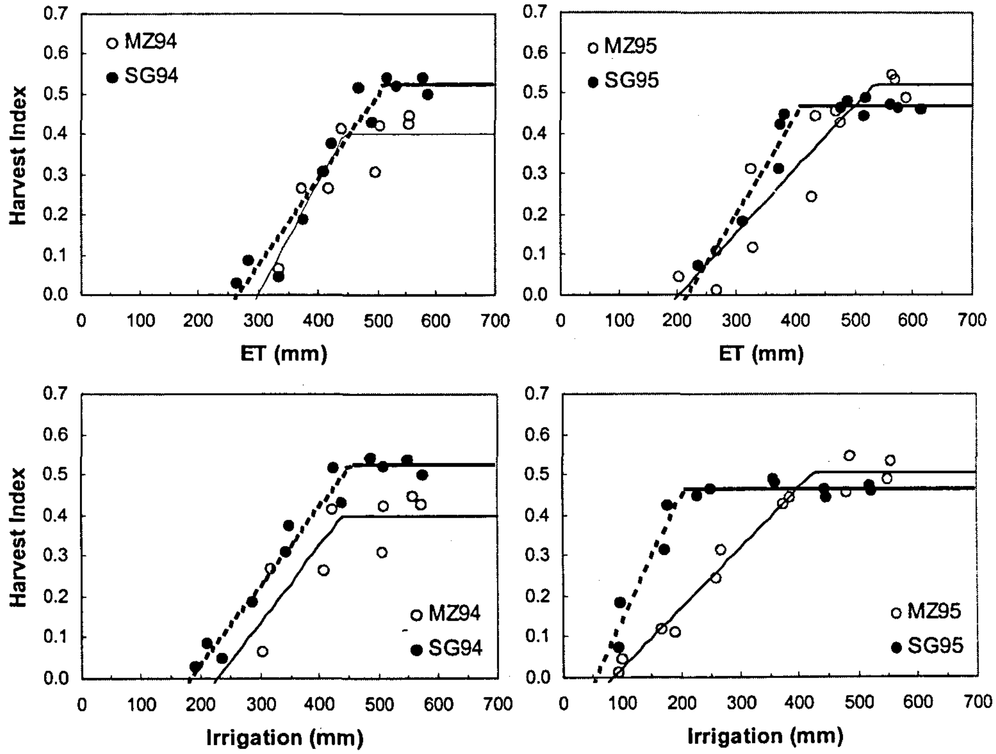

Fig. 2.12. Harvest index (HI) *vs.* seasonal evapotranspiration (ET) and *vs.* seasonal irrigation for maize (MZ) and sorghum (SG) in1994 and 1995.

3.13. Water use efficiency

Above-ground biomass (WUE_{DM}) and yield (WUE_Y) water use efficiency, expressed as the ratio of above-ground biomass and grain yield to seasonal crop ET, respectively were lower in 94 than in 95 for corresponding water applied treatments (Fig. 2.13). In 1994 WUE_{DM} and WUE_Y averaged 1.49 and 0.56 g m^{-2} mm^{-1} across irrigation treatments and crops, whereas in 1995 those averages were 2.48 and 0.96 g m^{-2} mm^{-1}. The low values of 1994 may be attributed to 1) the adverse effects on yield of the water and salt stress and 2) to a high soil evaporation component.

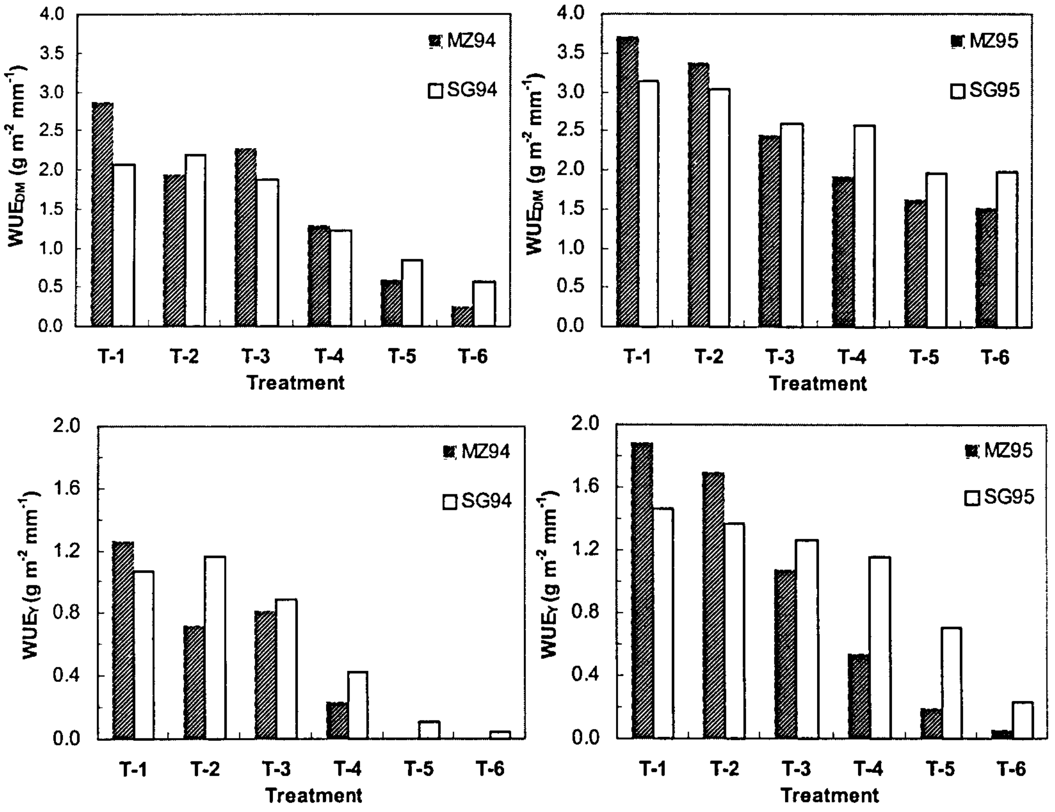

Fig. 2.13. Above-ground biomass (WUE_{DM}) and yield (WUE_Y) water use efficiency in the different irrigation treatments for maize (MZ) and sorghum (SG) in 1994 and 1995.

Within each year there were no significant differences between crops in WUE_{DM} and WUE_Y. Even though not significant, WUE tended to be greater in maize at high irrigation levels and in sorghum at the low range of irrigation amounts. Singh and Singh (1995) also reported sorghum having greater WUE than maize for a wide range of deficit irrigation treatments. Hattendorf *et al.* (1988) found similar values of WUE for both maize and sorghum grown under favorable soil moisture conditions.

In both years, WUE_{DM} and WUE_Y were less in maize than in sorghum in those treatments where less water was applied. Rhoads and Bennet (1990) reported, that water stress imposed at any growth stage on corn would generally lower the efficiency of the water used in transpiration. Eck (1986) also found no evidence of an increase in WUE when irrigation was withholded during the vegetative or the grain filling stages of growth in maize (least sensitive stages). In contrast, Singh and Singh (1995) found sorghum WUE to increase for a range of moderate water stresses and decreased only for a severe water stress.

3.14. Irrigation Water Use Efficiency

The irrigation water use efficiency (IWUE), expressed as the ratio of grain yield to total net irrigation water applied is shown in Fig. 2.14. IWUE was significantly lower in 1994 than in 1995. In 1994, IWUE decreased with increasing water deficits in both crops, but no significant differences ($P>0.05$) were found between maize (average = 0.51 g m^{-2} mm^{-1}) and sorghum (average = 0.67 g m^{-2} mm^{-1}).

In 1995 marked differences in IWUE between maize and sorghum were found. IWUE in maize linearly decreased with decreasing amount of water applied in irrigation (R^2 = 0.93). In contrast, IWUE in sorghum remained stable for decreasing amounts of water applied for a wide range of deficit irrigation treatments (T-1 to T-5), and only significantly decreased at T-6.

For similar yield and seasonal ET, the differences in IWUE responses between crops can be explained by the greater ability of sorghum to extract water to lower soil water contents and to greater depths in the profile.

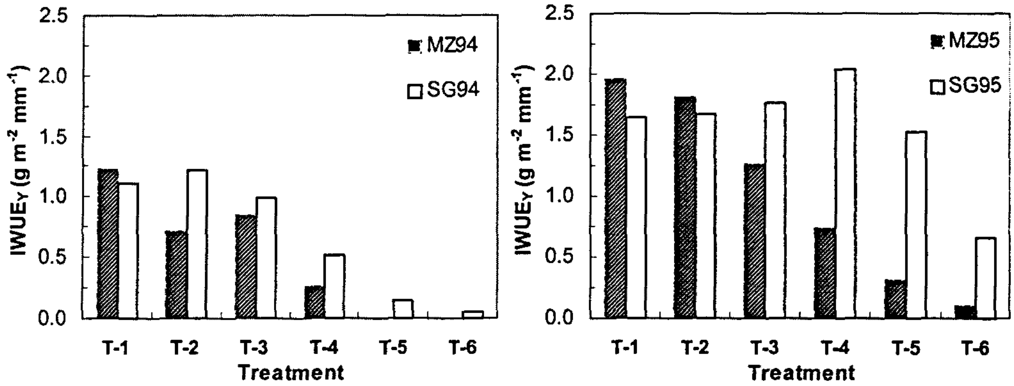

Fig. 2.14. Irrigation water use efficiency (IWUE), expressed as the ratio of grain yield to seasonal irrigation applied, in the different irrigation treatments for maize (MZ) and sorghum (SG) in 1994 and 1995.

4. CONCLUSIONS

The variable water supply imposed by the sprinkler line-source produced a gradual decrease of ET in both years and crops. Vegetative and reproductive growth and yield were affected by the water deficits. Vegetative and reproductive growth and yield were more affected in 1994 than in 1995 in both crops.

In 1994, the combination of water and salt stress severely affected crop development and yield, with no significant differences between the two crops in their response to the variable water supply.

In 1995, maize and sorghum differed in their responses to deficit irrigation treatments. Under full irrigation (T-1), maize gave greater yield than sorghum. Water deficits reduced vegetative growth and yield in maize more than in sorghum, giving higher yields of sorghum than maize for a given irrigation deficit. This resulted in an advantage for sorghum as the water deficit increased. These results agree with the reputed drought tolerance of sorghum (Krieg and Lascano, 1990; Mastrorilli *et al.*, 1995; Garrity *et al.*, 1982a) and with other studies (Muchow, 1989; Singh and Singh, 1995; Norwood and Currie, 1997) comparing maize and sorghum.

Water deficit reduced grain yield more than total above-ground biomass, as it is reflected in the decrease in HI. The decrease in yield was associated with a significant reduction in seed number and to a lesser degree in a reduction of mean kernel weight in both crops.

The greater yields of sorghum under water deficit conditions were achieved as it had a greater above-ground biomass and a higher harvest index. The shorter life-cycle of sorghum enables it to escape better from the water deficit, and this attribute may contribute to its yield stability. Moreover, sorghum had a greater water extraction capacity from soil deeper layers than maize which extracted more water from upper layers of the soil profile. As it has been assessed from soil water extraction patterns, sorghum presumably had a more extensive and deeper root system than did maize. Sorghum had foliage characteristics, notably a low K (extinction coefficient for PAR) and more erect leaves, which could enable it to cope better than maize with water stress and confer better adaptation to drought.

The results from the study show that maize was superior to sorghum when water was freely available (T-1), while sorghum showed less reduction than maize in its yield and HI under water limiting conditions. The greater soil water extraction of sorghum under drought, caused the lack of significant differences in WUE_{DM} and WUE_Y between maize and sorghum. IWUE in maize decreased markedly with decreasing amounts of water applied, whereas in sorghum IWUE was stable over a wide range of water applied below that of full irrigation.

Deficit irrigation strategies should take into account the soil characteristics since the soil type affects water use, growth and yield (Tolk *et al.*, 1997). Stockle and James (1989) analyzed irrigation strategies using crop models and suggested that slight irrigation deficits could provide higher net benefit than full irrigation in some crops and soil types, but that large irrigation deficits would never be advantageous. They found that large soil water holding capacity, high soil water content at planting and deep root exploration to be important for successful implementation of deficit irrigation (Stockle and James, 1989)

Assuming equal net returns per unit of yield produced for both crops, the results of this study suggest that maize should be preferred to sorghum if water supply is not limiting, but sorghum could be an economically alternative crop to maize under conditions of inadequate water supply grown in a similar soil type in the semiarid conditions of Northeast Spain.

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