

# Analysis of maize growth for different irrigation strategies in northeastern Spain

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## Abstract

Water availability is the key factor determining maize yields in NE Spain. Irrigation is needed to obtain economic yields but it is costly and water supply is sometimes insufficient. The aim of this research was to test a simple simulation model for evaluating different irrigation strategies, especially under water-limited conditions. The LINTUL model was adapted and parameterized using experimental data from the 1995 season. Most parameters were obtained from experiments, although some were taken from the literature. This model is based on the concept of light use efficiency, incorporates a soil water balance and simulates phenology, crop leaf area, biomass accumulation and yield. It was tested on independent data from the 1995 and 1996 seasons under different irrigation treatments. The model predicted the flowering date within  $\pm 5$  days of the observed values. Leaf area index was predicted satisfactorily, except under extreme water-stress conditions, where it was overestimated. In general, soil moisture content and yield were accurately predicted. In the 1996 experiment measured yields ranged from 6.4 to 13.6 t ha<sup>-1</sup> and simulated yields from 6.5 to 12.2 t ha<sup>-1</sup>. These results show that the LINTUL model can be used as a tool for exploring the consequences on maize yields of different irrigation strategies in NE Spain. Analysis of the model identified a process that strongly affects yield loss due to drought, but for which present understanding is still insufficient: the effects of drought on leaf senescence and canopy architecture. © 2000 Elsevier Science B.V. All rights reserved.

**Keywords:** Maize; Irrigation; Water stress; Simulation model

## 1. Introduction

Maize (*Zea mays* L.) is one of the major summer crops grown in the Mediterranean region. The scarce and highly variable precipitation in this region makes efficient planning of water use

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for irrigation necessary for most summer crops. Extensive research has been carried out on crop responses to water-limited conditions. Maize has been reported to be very sensitive to drought, particularly during flowering (Begg and Turner, 1976; Otegui et al., 1995). NeSmith and Ritchie (1992a) reported yield reductions exceeding 90% caused by water-deficit during flowering in maize. The degree of yield reduction is determined by the timing, severity and duration of the water deficit (Hsiao, 1990). It is difficult to plan a deficit irrigation scheme for maize without causing yield reductions (Rhoads and Bennett, 1990; Lamm et al., 1994).

To determine optimal irrigation strategies one could choose to do a large number of site-specific, long-term experiments. However, field experiments are time consuming and costly. Another option, therefore, is to integrate our present understanding of the processes responsible for crop response to water availability in crop simulation models. In this way the number of field experiments is reduced, while the model may be used in an exploratory manner to assess irrigation scenarios that can not be economically evaluated by experimentation and thus help improve irrigation management.

Several crop models have been developed for crop-water relationships differing in approach and detail (Jones and Kiniry, 1986; Spitters and Schapendonk, 1990; Amir and Sinclair, 1991; Jefferies and Heilbronn, 1991; Muchow and Sinclair, 1991; Stockle et al., 1994). The level of complexity

required depends on the aims of the model. Simple models are often appropriate when aiming for yield prediction (Maas, 1993). Such simple models are more easily parameterized and often show a more robust behaviour than complex models. In this paper complexity of the model is kept to a minimum and additional phenomena or processes were only incorporated if they were expected to improve the predictive ability of the model.

For this purpose, we have selected the generic crop growth model LINTUL, which calculates crop growth as the product of light interception and light use efficiency, and includes a water balance (Spitters and Schapendonk, 1990).

The objectives of this paper were to parameterize and test the LINTUL model, in order to develop a tool for exploring the consequences for maize yield of different irrigation strategies in the dry conditions of the Ebro Valley in northeast Spain. For model parameterisation and testing, we carried out field experiments in the region, in which drought was imposed at various times and various severities.

## 2. Field experiments

Three experiments (Table 1) were conducted in Zaragoza, northeast Spain (latitude 41° 43' N, longitude 0° 49' W, altitude 225 m) during the growing seasons of 1995 and 1996, to study the response of maize (cv. Prisma 700) to water deficits. The soil, developed from alluvial deposits,

Table 1  
Summary of crop data and irrigation treatments in experiments used for the parameterisation and testing of the LINTUL model<sup>a</sup>

	Experiment		
	Parameterisation (PHS-95)	Testing (PHS-96)	Testing (CS-95)
Crop emergence date (DOY)	145	145	146
Plant density (pl m <sup>-2</sup> )	8.2	8.0	8.2
Row spacing (m)	0.75	0.75	0.75
Harvest date (DOY)	278	290	275
Irrigation treatments	III, IsI, IsI, sII, Iss, ssI, sIs, sss, rrr	III, IIs, IsI, sII, Iss, ssI, sIs, sss, rrr	T1, T2, T3, T4, T5, T6

<sup>a</sup> Dates are expressed in day of the year (DOY). CS, continuous stress experiment; PHS, phases stress experiment. The different irrigation treatments are indicated with codes that are explained in the text.

was classified as *Typic Xerofluvent*. The depth that may be rooted is determined by a gravel layer occurring between 1.0 and 1.7 m. The texture is sandy loam in the 0.0–0.5 m top soil and loam to sandy loam below. The volumetric moisture content at field capacity (0.03 MPa) and permanent wilting point (1.5 MPa) in each 0.3 m layer to 0.9 m depth were measured using pressure plates (Richards, 1949). The values of field capacity and wilting point hardly differed in the three measured layers in the 0–0.9 m soil profile, and were averaged as 27 and 9%, respectively.

Soil water content was monitored gravimetrically and/or by neutron probe in each 0.2 or 0.3 m layer down to 1–1.2 m depth during the growing season. The average moisture content of the profile used for comparison with the model was calculated from the soil water contents in each layer up to 0.9 m depth, taking into account the layer thickness. Experimental details are given in Table 1. Crop development was recorded from emergence to physiological maturity. Plant height and the fraction of photosynthetically active radiation (PAR) intercepted by the crop were measured at 1- to 2-week intervals. Intercepted PAR (IPAR) was calculated from PAR values that were measured below and above the crop canopy with a portable tube solarimeter (Model Delta T-Devices Ltd). To eliminate the effect of solar altitude on the interception values the measurements were taken at noon on cloudless days. Leaf area index (LAI) and specific leaf area (SLA) were measured at flowering. Shoot biomass and its partitioning among the different plant organs was determined biweekly by harvesting 0.5 m<sup>2</sup> from each plot. At physiological maturity, total above ground biomass and grain yield was obtained.

Electrical conductivity of 1:5 soil–water extracts (ECs) was measured to assess possible salinity problems during the experimental period. Cultural practices comprise high input conditions to avoid nutritional limitations. Weeds, insects and diseases were controlled according to common practices in the area.

Irrigation scheduling for the well-irrigated treatments was calculated from the reference evapotranspiration (ET<sub>0</sub>) measured in a weighing lysimeter located nearby multiplied with a time-de-

pendent crop coefficient (Doorenbos and Pruitt, 1977). Rainfall during the growing season was 35 mm in 1995 and 103 mm in 1996, which represents 5 and 16% of the total crop water requirements, respectively.

### *2.1. Water stress during different growth phases (phases stress experiments = PHS)*

Field experiments were carried out in 1995 and 1996 to study the effects of a moderate water stress at different stages of crop development in maize.

The growing season was divided into three phases: (1) from emergence to tassel emergence; (2) from tassel emergence to milk stage of grain; and (3) from milk stage to physiological maturity. In each of the phases either irrigation to meet the potential evapotranspiration of the crop (I) or about one third of this amount (s) was supplied, by skipping some of the irrigation events or applying a lower depth. All possible combinations of these treatments were applied (III, IIs, IsI, sII, Iss, ssI, sIs, sss). An additional treatment (rrr), consisting of half of the water used in the well-irrigated treatment, was included. Irrigation management in the well-irrigated treatment was based on the common irrigation practices in the area, which consist in flood irrigation at 10–14 days interval.

The experimental design was a randomised block, with nine treatments and three blocks. Soil ridges delimited plots of 50 m<sup>2</sup>. Irrigation was applied from 200 mm diameter gated pipes with a total discharge rate in each plot of 3.4 l s<sup>-1</sup>. Total water applied at each irrigation was measured with a volumetric flow meter. The depth of water applied in each irrigation varied from 32.0 to 79.3 mm. The III treatment received a total of nine and eight irrigations during the growing season in 1995 and 1996, respectively. The rest of the treatments received between three and seven irrigations (Table 2).

### *2.2. Continuous water stress experiments (continuous stress experiment = CS)*

In 1995 the sprinkler line-source technique (Hanks et al., 1976) was used to study the effects of a continuous water stress on maize. The sprin-

Table 2

Irrigation dates (day of the year, DOY) and amount of water applied (mm) in the different irrigation treatments in the phases stress experiments in 1995 (PHS-95) and 1996 (PHS-96).

Treatment (DOY)	Phase 1			Phase 2			Phase 3			Total
	165	177	188	199	209	218	234	248	262	
<i>PHS-95</i>										
III	79.3	65.2	60.7	60.2	65.0	65.0	60.0	57.4	55.6	568.4
Is <sup>I</sup> a	79.3	65.2	60.7	60.2			60.0	57.4	55.6	438.4
IsI	79.3	65.2	60.7		52.0		60.0	57.4	55.6	430.2
sII		65.2		60.2	65.0	65.0	60.0	57.4	55.6	428.4
Iss	79.3	65.2	60.7		52.0			57.4		314.6
sII		65.2			52.0		60.0	57.4	55.6	290.2
sIs		65.2		60.2	65.0	65.0		57.4		312.8
sss		65.2			52.0			57.4		174.6
rrr	79.3		60.7		65.0		60.0		55.6	320.6
	Phase 1			Phase 2			Phase 3			
	159	180	192	204	218		229	243	257	
<i>PHS-96</i>										
III	63.3	58.4	69.7	70.7	66.0		55.2	59.7	62.4	505.3
IIs	63.3	58.4	69.7	70.7	66.0			59.7		387.8
IsI	63.3	58.4	69.7		32.0		55.2	59.7	62.4	400.6
sII		58.4		70.7	66.0		55.2	59.7	62.4	372.2
Iss	63.3	58.4	69.7		32.0			59.7		283.1
ssI		58.4			32.0		55.2	59.7	62.4	267.5
sIs		58.4		70.7	66.0			59.7		254.7
sss		58.4			32.0			59.7		150.0
rrr	63.3		69.7		66.0			59.7		258.7

<sup>a</sup> In 1995 two treatments were subjected to deficit irrigation in phase 2: the IsI received one irrigation in the middle of phase 2, whereas the IsI treatment received one irrigation at the beginning of phase 2.

kler line-source provided adequate water near the sprinkler line throughout the growing season while applying a decreasing quantity of water with increasing distance perpendicular to the line-source. To define different irrigation treatments the gradient of water applied was divided into six parts (T1–T6). Water stress developed progressively during the growing season in the five sub-optimal irrigation treatments (T2–T6). Irrigation was applied every 2–4 days to meet the potential evapotranspiration demand of a maize crop at the rows nearest to the line source (T1). Catchment cans installed across the field at a spacing of 2.25 m were read after each irrigation. The degree of deficit irrigation for each treatment can be inferred from Fig. 1, which shows the amount of water applied to the different treatments during

the growing season. A total of 27 irrigations were applied during the irrigation season. The total seasonal amount of irrigation water applied in T1 was 551.2 mm.

### 3. Model description

The original version of the LINTUL model was described by Spitters and Schapendonk (1990). LINTUL is based on the fact that crop growth rate under favourable conditions is proportional to the amount of light intercepted by the canopy (Monteith, 1977). The model is implemented in the Fortran simulation translator, FST (Rappoldt and Van Kraalingen, 1996). Simulations run at a time step of 1 day, which is based on the charac-

teristic time coefficient of the model. A code listing is available upon request from the authors of the paper.

Required inputs for the model include daily weather data (maximum and minimum temperature, global radiation, rain, vapour pressure and wind speed), crop management data (plant density and day of emergence), crop parameters, the soil moisture retention characteristics (soil water content at saturation, field capacity, wilting point and air dryness) and the initial soil water content.

The model consists of two major parts, the plant growth component and the soil water component, which may induce a reduction in growth rate.

### 3.1. Crop growth under optimal water supply

The dry weights of the different plant organs (leaves, stems, roots and grains) are the state variables in the crop growth model and are obtained by integration of their growth rates over time. The daily crop biomass increment is calculated as the product of the amount of IPAR by the crop and the light use efficiency (LUE). In the absence of drought, LUE is constant. Light interception by the crop is modelled as a function of its LAI and a constant light extinction coefficient ( $K$ ), using Beer's law. During the early stages of growth, leaf area increases exponentially as a function of temperature. In later stages, leaf area growth is

calculated as the increase in leaf weight times a constant specific leaf area. Leaf senescence due to ageing and self-shading is taken into account in computing the net increase in leaf weight. The dry matter produced is partitioned among the various plant organs, using partitioning factors defined as a measured function of the thermal time. For example, grain yield is calculated as total dry matter growth multiplied by the thermal-time dependent fraction of dry matter allocated to the storage organs.

### 3.2. Effects of drought on crop growth

In the model, water-limiting conditions have two effects on the crop: reduction of growth rate and change in allocation pattern. Crop growth is reduced proportionally via the ratio of actual to potential transpiration. The critical soil water content below which transpiration rate is reduced below its potential value depends on crop sensitivity to drought and the evaporative demand of the atmosphere (Driessen, 1986). Dry matter partitioning changes in favour of root growth during the vegetative phase (Munns and Pearson, 1974) when the ratio of actual to potential transpiration falls below 0.5 (Van Keulen et al., 1981). No effects of drought on crop morphology ( $K$ , SLA) and leaf senescence are assumed in the model.

### 3.3. Soil water balance

Soil water balance is calculated using one soil layer, which increases in thickness depending on root depth (Van Keulen, 1986). Root growth causes exploration of the water in depth, until the maximum rooting depth or soil depth is reached. Newly explored soil depth is assumed to be at field capacity initially. The daily change in soil moisture content in the rooting zone is calculated as the net result of water gain from irrigation and rainfall, minus water loss by crop transpiration, soil evaporation, runoff and deep percolation. Daily values of irrigation and rainfall are inputs needed in the model. Percolation is calculated as the amount of water in excess of field capacity that drains below the root zone. Runoff occurs if maximum drainage capacity is exceeded.

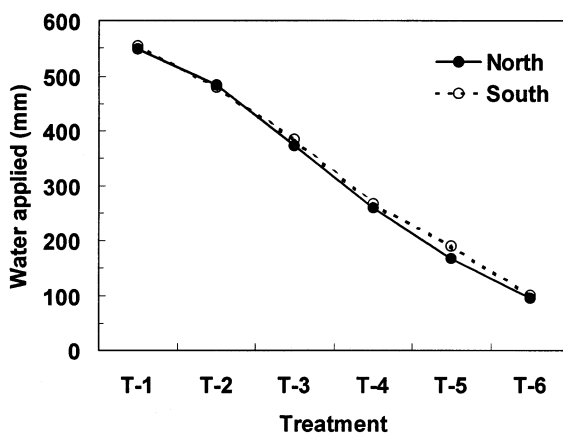


Fig. 1. Total amount of water applied by the sprinkler line-source to its north side and south side in all the treatments, in the CS-95 experiment.

Table 3

Values of crop and soil parameters used in the study

Symbol	Parameter	Unit	Value	Source
<i>Crop parameters</i>				
$K$	Light extinction coefficient	—	0.6	Boons-Prins et al., 1994
LUE	Light use efficiency	g DM MJ <sup>-1</sup> PAR	4.6	Exp. PHS-95
SLA	Specific leaf area	m <sup>2</sup> g <sup>-1</sup>	0.016	Exp. PHS-95
$T_{\text{base}}$	Base temperature	°C	8	Warrington and Kanemasu, 1983
$T_{\text{sum } 1}$	$T_{\text{sum}}$ from emergence to anthesis ( $T_{\text{base}} = 8^{\circ}\text{C}$ )	°C day	1000	Exp. PHS-95
$T_{\text{sum } 2}$	$T_{\text{sum}}$ from emergence to maturity ( $T_{\text{base}} = 8^{\circ}\text{C}$ )	°C day	1750	Exp. PHS-95
ROOTDM	Maximum root depth	m	0.9	Exp. PHS-95
TRANSC	Transpiration constant (level of drought tolerance)	mm	1.8	Driessen, 1986
<i>Soil parameters</i>				
WCST	Water content at full saturation	m <sup>3</sup> m <sup>-3</sup>	0.45	Exp. PHS-95
WCFC	Water content at field capacity (0.03 MPa)	m <sup>3</sup> m <sup>-3</sup>	0.27	Exp. PHS-95
WCWP	Water content at wilting point (1.5 MPa)	m <sup>3</sup> m <sup>-3</sup>	0.09	Exp. PHS-95
WCAD	Water content at air dryness	m <sup>3</sup> m <sup>-3</sup>	0.03	Exp. PHS-95

Potential evapotranspiration is calculated with the Penman equation (Penman, 1948). Potential transpiration is a fraction of this rate, equal to fractional light interception calculated using Beer's law. The ratio of maize transpiration to Penman transpiration is introduced in the model to obtain the potential maize transpiration. This ratio ranges from 1.0 to 1.2 depending on ground cover (Doorenbos and Pruitt, 1977). Actual transpiration rate is calculated from its potential value and the soil water status. Actual evaporation is calculated from its potential value, the soil water status and an additional exponential decrease after days without rain or irrigation. The exponential decrease is a simplified implementation of Ritchie's concept of evaporation reduction proportional to the square root of the number of days since the last rainfall with a fixed wet stage of 1 day (Ritchie, 1972).

#### 4. Model parameterisation

A part of the experimental data was used for parameterisation of the model, whereas another independent portion of the data was reserved to test the model. Experiment PHS-95 was chosen for model parameterisation because it had a high

frequency of detailed field measurements. Values that could not be obtained from this experiment were taken from the literature. A list of the crop and soil parameters, resulting from the parameterisation described below, with their values is summarised in Table 3.

##### 4.1. Crop parameters

###### 4.1.1. Light extinction coefficient

Extensive measurements on spring wheat cv. Yecora 700 24 (Robertson and Giunta, 1994), had revealed no effects of drought on the light extinction coefficient. In contrast, in our own experiments light extinction measured at noon at anthesis (when  $K$  has the lowest value) was found to be affected by the different irrigation treatments ( $K$  — fully irrigated, 0.5;  $K$  — deficit irrigation, 0.2–0.3). Extensive measurements (diurnal and over the season) would be needed to allow a parameterisation of the effect of drought on  $K$ . In the model, due to lack of experimental data,  $K$  was assumed to be constant throughout the growing season, with a value of 0.6 (Boons-Prins et al., 1994). This value applies to global total daily light interception and is an average over the whole photoperiod.

#### 4.1.2. Light use efficiency

LUE was obtained by simple linear regression of total crop biomass, measured at different times in the season, and cumulative light interception, in the well-irrigated treatment. Total crop biomass was computed as the sum of measured above ground biomass and estimated root biomass. Root biomass was estimated using the observation that the ratio of root growth to total

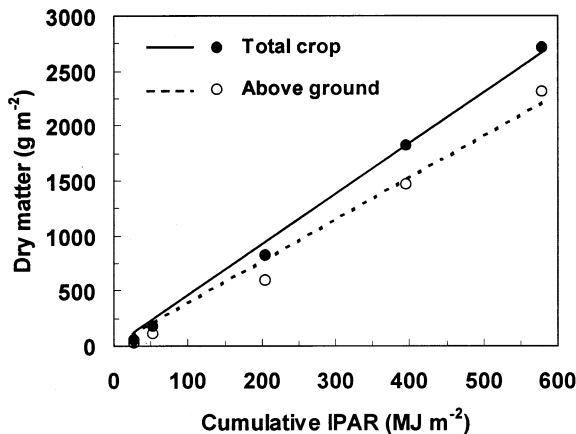


Fig. 2. Relationship between cumulative dry matter (total crop biomass and above-ground biomass) and cumulative intercepted PAR (IPAR) by the crop, in the well-irrigated treatment in the PHS-95 experiment. Lines represent fitted linear regressions forced through the origin.  $y = 4.61x$ ,  $R^2 = 0.995$  (—);  $y = 3.82x$ ,  $R^2 = 0.984$  (---).

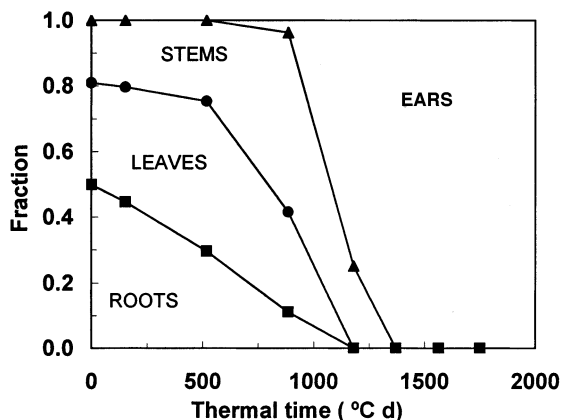


Fig. 3. Fraction of the dry matter partitioned to the different plant organs (roots, leaves, stems and ears) as a function of thermal time, in the well-irrigated treatment in the PHS-95 experiment. The fraction leaves includes blade plus sheath.

growth decreases from 0.5 to 0 from emergence to anthesis (Penning de Vries et al., 1989).

Daily total incident PAR was multiplied by the fraction of light that was intercepted (values between measurements were linearly interpolated) to obtain the daily IPAR by the crop. The sum of these daily values gave the total cumulative IPAR by the crop. LUE was then calculated as the slope of the regression line of cumulative total crop biomass on cumulative IPAR (Fig. 2). The regression line was forced through the origin, because of the assumed direct proportionality of light interception and growth. Post-anthesis harvests were excluded because of unmeasured weight loss due to fallen leaves. A value of LUE of 4.6 g DM/MJ IPAR was obtained. A similar value (4.5) has been found by Cabelguenne et al. (1990) in southern France. Lower values have been reported for maize in different experiments (3.5 g MJ<sup>-1</sup>, Maas, 1993; 4.0 g MJ<sup>-1</sup>, Stockle et al., 1994) but these values refer only to above ground biomass. Values obtained in the literature agree well with the value of 3.8 g MJ<sup>-1</sup> found in our experiment when only above ground biomass was considered (Fig. 2).

#### 4.1.3. Dry matter partitioning

Partitioning of the daily increment of dry matter among leaves, stems, roots and storage organs was related to thermal time (Fig. 3). Thermal time was calculated (Table 3) with a base temperature of 8°C (Warrington and Kanemasu, 1983; Cabelguenne et al., 1990). Roots were not measured in the field experiment. Partitioning between shoot and root was therefore, assumed to be similar to earlier reports (Penning de Vries et al., 1989; Boons-Prins et al., 1994). The pattern of allocation to leaves, stems and storage organs was derived as the fraction of new above-ground biomass production allocated to the different plant organs between two subsequent harvests (Fig. 3). This above-ground allocation pattern hardly varied among treatments. Decreases in leaf and stem weight at late growth stages due to senescence and translocation were assumed to indicate that no more biomass was allocated to these organs.

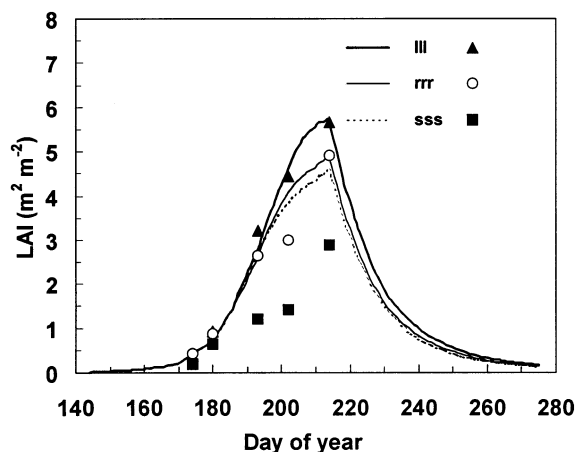


Fig. 4. Measured (symbols) and calculated (lines) leaf area index (LAI) values in treatments III, rrr and sss of the PHS-95 experiment.

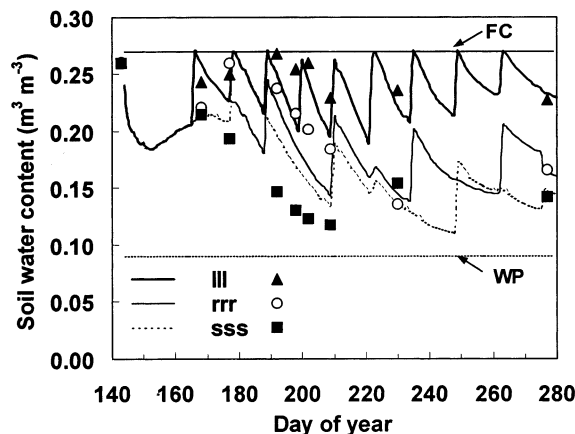


Fig. 5. Measured (symbols) and calculated (lines) volumetric soil water content in the 0–0.9 m soil profile in treatments III, rrr and sss of the PHS-95 experiment. Horizontal lines represent soil water content at field capacity (FC) and wilting point (WP).

#### 4.1.4. Specific leaf area

The value of SLA increases with age, but drought may reduce its value (Ludlow, 1975). However, Habekotté (1997), working with oilseed rape, found that including the dynamics of SLA in a crop model did not improve the simulation of dry matter in comparison with using an average value of SLA. Therefore, a constant value of  $0.016 \text{ m}^2 \text{ g}^{-1}$ , measured at anthesis in the well-ir-

rigated treatment, was used in the model. The same value has been reported for maize (Sibma, 1987). No effect of water stress on SLA is considered in the model.

#### 4.1.5. Leaf senescence

Water stress can accelerate leaf senescence (Ne-Smith and Ritchie, 1992b). Despite the differences in leaf senescence visually assessed among treatments in the field experiments, lack of quantitative data did not allow us to establish a relationship between leaf senescence and irrigation treatment. In the model leaf senescence occurs due to ageing (through temperature and thermal time) and due to shading (through LAI), but the effect of water stress on leaf senescence is not considered.

#### 4.2. Soil parameters

Soil water content at field capacity ( $0.27 \text{ m}^3 \text{ m}^{-3}$ ) and wilting point ( $0.09 \text{ m}^3 \text{ m}^{-3}$ ) were obtained using pressure plates (Richards, 1949). Soil water content at saturation ( $0.45 \text{ m}^3 \text{ m}^{-3}$ ) was estimated from porosity measurements and at air dryness ( $0.03 \text{ m}^3 \text{ m}^{-3}$ ) as one third of wilting point.

#### 4.3. Evaluation of the model parameterisation

The parameterisation was checked first by running the model for the conditions of the PHS-95 experiment. The calculated LAI satisfactorily matched the measured values from the experiment for different treatments except for the treatment subjected to deficit irrigation during all of the three developmental phases (sss), where LAI was overestimated (Fig. 4). Fig. 5 shows the averaged measured and simulated soil water content of the total profile for the treatments HI, rrr and sss at several dates during the crop season. Soil water content was simulated accurately at the end of the crop season. Throughout the season the predicted soil water content did not exactly match the measured values from the experiment, but the experimental data were included in the general trend of data.



Fig. 6 shows the measured and calculated above-ground biomass at anthesis (Fig. 6a) and yield at maturity (Fig. 6b) for all the treatments of the PHS-95 experiment. The model correctly showed the trend of yield reduction under a decreasing amount of irrigation applied. In general, good agreement was observed between measured and calculated yields, differing on average by 23%. In six out of nine treatments the differences between the calculated and the observed values were within 5%, but deviations for the remaining three treatments (sss, Is'I and Iss) amounted to 60% and were significant. Measured yields had a high variability among replicates. These compari-

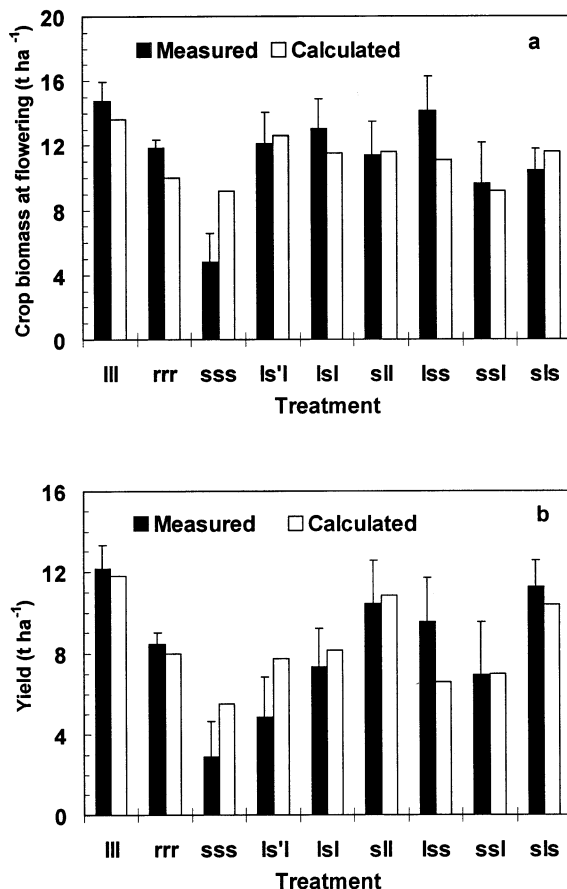


Fig. 6. Measured and calculated above ground biomass at flowering (a) and final yield (b) in all treatments of the PHS-95 experiment. Yield (oven dried weight) is expressed as the whole ear (grain + cob). For treatment details see text. Vertical lines represent the standard errors of the mean (S.E.).

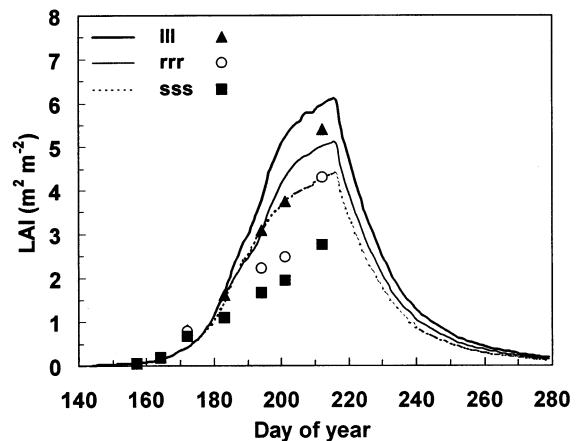


Fig. 7. Measured (symbols) and simulated (lines) leaf area index (LAI) in treatments III, rrr and sss of the PHS-96 experiment for model testing.

sons provide some information about the reasonableness of the model structure. It is however, not an independent model test. Testing of the model on independent data is described in the next section.

## 5. Model testing

After parameterisation the model was tested against independent data from the CS-95 and PHS-96 experiments (Table 1). The model was tested with respect to: date of flowering, leaf area index, soil water content, crop biomass and yield.

The date of flowering was simulated within 2 days of the observed dates in the well-irrigated treatments. In the water-deficit treatments, flowering was delayed between 2 and 5 days compared with the model results. This delay was not predicted by the model, because it assumes phenology to be only dependent on thermal time, so effects of water stress on phenology are not taken into account. However, in maize, water deficit can delay anthesis and physiological maturity. Ne-Smith and Ritchie (1992a) reported a delay in anthesis of up to 15 days in maize grown under water-limited conditions.

Fig. 7 shows simulated LAI and LAI estimated from IPAR measurements in the PHS-96 experi-

ment, for the III, rrr and sss treatments. Up to 45 days after sowing (day of year (DOY), 183), LAI was simulated well for all the treatments, and for the rest of the season it was simulated satisfactorily in the well-irrigated treatments. In the deficit irrigation treatments, increased leaf senescence as a result of water stress caused LAI to decrease. Because the model does not account for the effect of water deficit on leaf senescence, LAI from 45

days after sowing was overpredicted. In the CS-95 experiment, the LAI was also overestimated for all the suboptimal irrigation treatments (T2 to T6; data not shown).

Measured and simulated soil water content at different dates were compared for the treatments III, rrr and sss in the PHS-96 experiment (Fig. 8). The measured soil water content data were included in the general trend of the model, but given the scarcity of the data no final conclusion can be extracted.

Measured and simulated yields and dry matter at maturity were compared for all the irrigation treatments of the PHS-96 and CS-95 experiments. The model correctly showed the trend of yield reduction under decreasing irrigation amounts. In the PHS-96 experiment, measured yields ranged from 6.4 to 13.6 t ha<sup>-1</sup> and simulated yields from 6.5 to 12.2 t ha<sup>-1</sup> in the different irrigation treatments (Fig. 9). Mean measured and simulated yields were 10.4 and 9.7 t ha<sup>-1</sup>, respectively. Lowest yields were obtained in the sss treatment, both measured (6.4 t ha<sup>-1</sup>) and simulated (6.5 t ha<sup>-1</sup>). Actual and simulated above-ground biomass had a similar relative magnitude of variation (data not shown). The model accurately estimated yields for the treatments subjected to: full irrigation (III), moderate water deficit (rrr) and severe water deficit (sss) during the three phases of the growing season (measured and simulated differing by 7%). However, grain yield was overestimated (measured and simulated differing by 25%) for the treatments subjected to deficit-irrigation during the flowering phase. In contrast, in the treatments with limited-irrigation during the vegetative phase, grain yield was underestimated (measured and simulated differing by 21%), irrespective of the amount of irrigation received at later stages.

In the CS-95 experiment (Fig. 10) the model correctly simulated the observed trend of yield reduction under the gradient of water applied, but the simulated decrease in yield was less pronounced than observed. Measured yields decreased from 13.6 t ha<sup>-1</sup> in the well-irrigated treatment (T1) to almost none (0.1 t ha<sup>-1</sup>) in the least irrigated treatment (T6). The model predicted a range of yields from 12.3 to 2.5 t ha<sup>-1</sup>

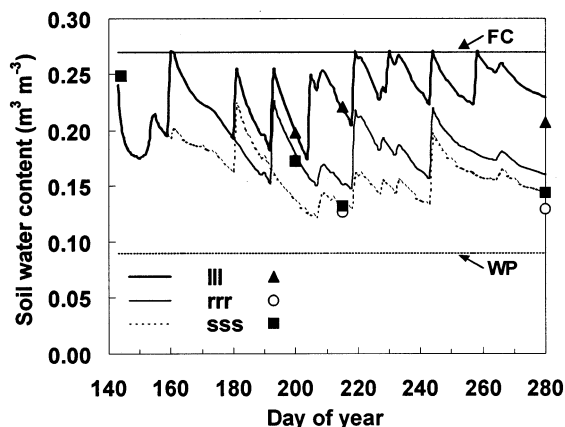


Fig. 8. Measured (lines) and simulated (symbols) volumetric soil water content in the 0–0.9 m profile depth in treatments III, rrr and sss of the PHS-96 experiment for model testing. Horizontal lines represent soil water content at field capacity (FC) and wilting point (WP).

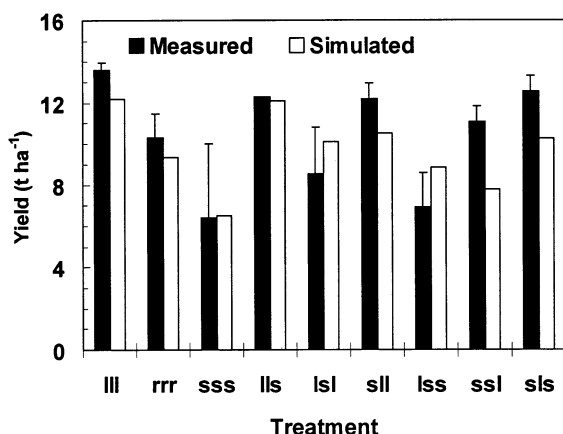


Fig. 9. Measured and simulated yields in all treatments of the PHS-96 experiment for model testing. Yield (oven dried weight) is expressed as the whole ear (grain + cob). For treatment details see text. Vertical lines represent the standard errors of the mean (S.E.).

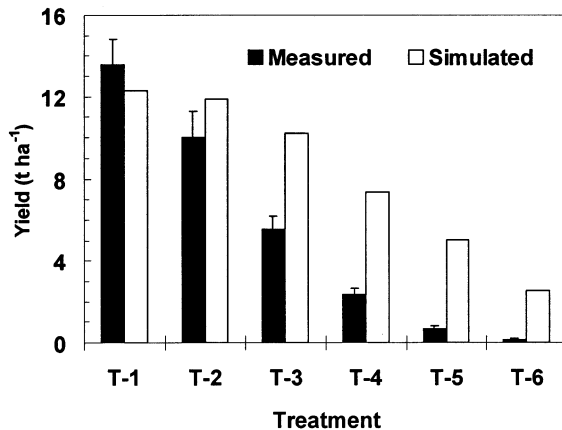


Fig. 10. Measured and simulated yields in all treatments of the CS-95 experiment for model testing. Yield (oven dried weight) is expressed as the whole ear (grain + cob). For treatment details see text. Vertical lines represent the standard errors of the mean (S.E.).

for T1 to T6. The important yield reduction can be partly explained by the combined effects of a shallow rooting pattern, high soil evaporation losses due to the high frequency irrigation and salinity on the crop in the line source sprinkler experiment. The effects of salt stress and shallow rooting system are not included in the model.

## 6. Sensitivity analysis

An analysis of the sensitivity of the simulated yield to +10% changes in the input parameters LUE,  $K$ , SLA, TRANSC (level of drought tolerance by the crop), root partitioning (fraction of the dry-matter partitioned to the roots as a function of thermal time) and leaf senescence (rate of leaf senescence) was performed using a simulated maize crop grown at Zaragoza at  $8.2 \text{ pl m}^{-2}$ . Four scenarios were evaluated, determined by the combination of two different soil types (sandy and clay soils) and two irrigation strategies (full irrigation and deficit irrigation). The full irrigation treatment consisted of applying irrigation amounts of 40 mm at weekly intervals, providing a total amount of water (640 mm) equivalent to the crop evapotranspiration ( $ET_c$ ). The deficit irrigation treatment received irrigation amounts of 40

mm at 14-day intervals, providing a total amount of water equivalent to half of the  $ET_c$ . The weather conditions of 1995 were used, together with an initial soil moisture content equivalent to field capacity. These scenarios provided a range of crop exposures to water deficit. Sensitivity analysis indicates how strongly the parameters ( $P$ ) affect the model results and also the degree of accuracy to which the tested parameters must be known. Sensitivity coefficients ( $SC$ ) are calculated as  $SC = (\Delta Y/Y)/(\Delta P/P)$ . Grain yield proved more than proportionately sensitive (sensitivity coefficient  $|SC| > 1$ ; Table 4) in all scenarios to change in LUE. Sensitivity was also high but to a lesser degree ( $0.5 < |SC| < 1$ ), to leaf senescence and  $K$ . In contrast, sensitivity of yield to change in SLA, TRANSC and root partitioning was low ( $|SC| < 0.5$ ) in all scenarios. Acceleration of leaf senescence resulted in a decrease in yield ( $SC$  negative) in all scenarios. Increase in  $K$  resulted in an increase in yield. Therefore, a possible decrease in  $K$  due to water stress would lead to a decrease in yield. The results indicate that the values of the LUE,  $K$  and leaf senescence rate should be accurately known, especially for limited irrigation conditions.

## 7. Discussion and concluding remarks

The results of this study reveal that the adapted LINTUL model gives satisfactory predictions of phenology, growth and yield for maize under different water conditions. The model simulates satisfactorily the time course of LAI under well-irrigated conditions, but overestimates it under water stress conditions. This suggests a need for studies aimed to quantifying the extent to which water stress can accelerate leaf senescence.

In the PHS-96 experiment yield was generally properly simulated, apart from an overestimation in the treatments with deficit irrigation during the flowering phase. This may be due to a particular sensitivity of maize to water stress during flowering. A number of studies indicate that anthesis may be a critical period for yield determination in maize (NeSmith and Ritchie, 1992a). Depending on the timing and intensity of drought, yield may

be reduced due to desynchronization of tasseling and silking, leading to impeded grain setting and kernel abortion (Struik et al., 1986). Plant adaptation to a moderate water stress after they had been exposed to a previous water stress could be responsible for the yield underestimation in the treatments with deficit irrigation during the vegetative phase. In the PHS-96 experiment, limited irrigation during the vegetative phase consisted mainly of a delay in the first irrigation. The delay in the first irrigation could have enhanced root growth in early stages and caused a better ability to withstand subsequent water stress. Boyer and McPherson (1976) observed that maize grown under a non-severe water stress during the vegetative period more efficiently withstood subsequent drought during the reproductive period.

A good agreement was found between simulated and observed yield for the well-irrigated treatment (T1) in the CS-95 experiment. The general yield overestimation for all the suboptimal irrigation treatments (T2 to T6) can be partly explained from the combined effects of a shallow rooting system and salinity in the experiments (not accounted for in the model). Data on soil water extraction during the growing season in the

CS-95 experiment showed that 70% of the plant water uptake took place from the 0.5 m top soil, 25% from the 0.5–0.7 m depth and only 5% was extracted from the 0.7–1.0 m depth. Even in the less irrigated treatments the crop failed to extract water from deeper soil layers. In the model, only one soil layer is considered and the maximum rooting depth is reached in all the treatments and only the total root biomass differs depending on the severity and timing of the water stress. The same rootable zone is used in the water balance for all treatments. It seems that the amount of water available to the crop was overestimated in the sprinkler irrigation experiment and therefore the effects on crop growth and yield were underestimated.

In the CS-95 experiment, the salinity level found in the top 0.3 m at crop emergence was below the maize threshold for salinity (Rhoades et al., 1992). However, the salinity level increased progressively both across the water gradient and in time. At harvest, the soil salinity level was found to be above the crop threshold in the water stressed treatments, and thus salt stress together with the water stress can be assumed to have occurred. In these treatments irrigation was in

Table 4

Sensitivity coefficients (SC) for the model yield (Y) in two irrigation scenarios and two soil types for changes of +10% in several crop parameters (P)<sup>a</sup>

Soil irrigation	SC = ( $\Delta Y/Y$ )/( $\Delta P/P$ )			
	Sandy		Clay	
	100% ET <sub>c</sub> <sup>b</sup>	50% ET <sub>c</sub> <sup>c</sup>	100% ET <sub>c</sub> <sup>b</sup>	50% ET <sub>c</sub> <sup>c</sup>
Reference yield (t ha <sup>-1</sup> )	11.3	6.7	12.0	8.4
<i>Parameters</i>				
LUE	1.24	1.52	1.42	1.32
K	0.51	0.88	0.65	0.67
SLA	0.22	0.48	0.38	0.29
TRANSC	-0.10	0.10	0.03	0.12
Root partitioning	-0.16	-0.01	0.00	0.00
Leaf senescence	-1.00	-0.91	-0.96	-0.88

<sup>a</sup> Parameters: LUE, light use efficiency; K, light extinction coefficient; SLA, specific leaf area, TRANSC, level of drought tolerance of the crop; root partitioning (fraction of the dry-matter partitioning to the roots as a function of thermal time); leaf senescence (rate of leaf senescence).

<sup>b</sup> Sixteen irrigations of 40 mm (total irrigation amount equivalent to ET<sub>c</sub>).

<sup>c</sup> Eight irrigations of 40 mm (total irrigation amount equivalent to half of ET<sub>c</sub>).

sufficient to meet the crop water requirements and to leach away soluble salts and therefore salts concentrated in the soil causing a salt stress as well as water stress in the plants. The effects of salinity on plant growth may have resulted in a reduction in the availability of water by lowering the osmotic potential (Fitter and Hay, 1987). Because the model does not simulate salinity effects, this explains the lower measured yields as compared with the simulated yields in the water-stressed treatments.

The model has helped identifying key processes in the response of maize to deficit irrigation strategies. Important differences in *K*, leaf senescence and root patterns have been assessed among irrigation treatments in the field experiments. The sensitivity analysis has shown the high sensitivity of the model to changes in *K* and leaf senescence. Therefore, the parameterisation of the effect of drought on *K*, leaf senescence and root patterns would probably improve the model performance under water stress. However, we conclude that the simple model gives satisfactory results considering its objectives and may be used for preliminary exploration of different irrigation strategies on maize yield in the Ebro Valley.

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